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Identifying Trends in the Temporal Signatures of Snow and its Impact on Catchment Hydrology over Europe during 2000-2022

von

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Statement of Authorship

I hereby certify that this master thesis has been composed by myself. I have not made the use of work of others or presented it here unless it is otherwise acknowledged in the text. All references and verbatim extracts have been quoted, and all sources of information have been specifically acknowledged.

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Acknowledgments

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Abstract

Studying snow is crucial as it impacts the hydrological cycle as well as the albedo, thereby the radiation budget. Therefore, changes in snow patterns can affect water availability, river flow patterns, and overall catchment water balance. This thesis aims to investigate trends in snowpack variables and their potential impacts on hydrological processes for snow-dominated and snow-rain-dominated regions in Europe. To identify trends in snowpack variables, European watersheds are classified into snow and snow-rain-dominated based on the snowfall fraction from the E-OBS meteorological data and a temperature and precipitation threshold. For these watersheds, snowfall (SF), and rainfall (RF) from in-situ meteorological data, snow cover duration (SCD) from MODIS satellite, and snow water equivalent (SWE) from ESA GLOBSNOW and GLWS2.0 products are analyzed to find trends and patterns during 2000-2022. Additionally, river discharge data at 862 Global Runoff Data Center (GRDC) stations were also compiled to investigate the impact of snow trends on changes in river flow and center of timing (CT). Results show increasing trends in SF, SWE, and discharge and decreasing trends in SCD in snow-dominated watersheds. Seasonally, the trends in both snowpack variables and rainfall are more pronounced in the winter than spring season. In addition, the increasing trends in mean discharge show a strong positive correlation with increasing SWE, particularly in the snow-dominated watersheds. However, the trends in CT indicate shifts of 2-3 days across many stations, suggesting an accelerated melting of snow attributed to rising temperatures. These trends align with the concurrent decreasing trend in SCD. Furthermore, water availability is assessed by comparing the change in snowpack and streamflow anomalies with total water storage (TWS) from GRACE satellites. Overall, the TWS shows a decreasing trend in the snow and snow-rain-dominated watersheds which we suggest is due to rapid snowmelt at high temperatures despite high SF and SWE. These results highlight the important changes in cryosphere–hydrological processes in the recent past, providing valuable information for integrated water resource management in Europe.

Zusammenfassung

Die Untersuchung des Schnees ist von entscheidender Bedeutung, da er sowohl den Wasserkreislauf als auch die Albedo und damit den Strahlungshaushalt beeinflusst. Daher können sich Änderungen in der Schneeverteilung auf die Wasserverfügbarkeit, Flussströmungsmuster und den gesamten Wasserhaushalt des Einzugsgebiets auswirken. Ziel dieser Arbeit ist es, Trends bei Schneedeckenvariablen und ihre möglichen Auswirkungen auf hydrologische Prozesse für schneedominierte und schneeregendominierte Regionen in Europa zu untersuchen. Um Trends in den Schneedeckenvariablen zu identifizieren, werden europäische Wassereinzugsgebiete auf der Grundlage des Schneefallanteils aus den meteorologischen E-OBS-Daten und eines Temperatur- und Niederschlagsschwellenwerts in schnee- und schneeregendominierte Wassereinzugsgebiete eingeteilt. Für diese Wassereinzugsgebiete werden Schneefall (SF) und Niederschlag (RF) aus meteorologischen In-situ-Daten, Schneebedeckungsdauer (SCD) vom MODIS-Satelliten und Schneewasseräquivalent (SWE) von ESA GLOBSNOW- und GLWS2.0-Produkten analysiert, um dies herauszufinden Trends und Muster im Zeitraum 2000–2022. Darüber hinaus wurden Flussabflussdaten an 862 Stationen des Global Runoff Data Center (GRDC) zusammengestellt, um die Auswirkungen von Schneetrends auf Änderungen des Flussflusses und des Center of Timing (CT) zu untersuchen. Die Ergebnisse zeigen zunehmende Trends bei SF, SWE und Abfluss sowie abnehmende Trends bei SCD in schneedominierten Wassereinzugsgebieten. Saisonal sind die Trends sowohl bei den Schneedeckenvariablen als auch bei den Niederschlägen im Winter ausgeprägter als im Frühjahr. Darüber hinaus zeigen die zunehmenden Trends im mittleren Abfluss eine starke positive Korrelation mit zunehmendem SWE, insbesondere in den schneedominierten Wassereinzugsgebieten. Allerdings deuten die CT-Trends an vielen Stationen auf Verschiebungen von 2-3 Tagen hin, was auf eine beschleunigte Schneeschmelze aufgrund steigender Temperaturen schließen lässt. Diese Trends stimmen mit dem gleichzeitigen rückläufigen Trend bei SCD überein. Darüber hinaus wird die Wasserverfügbarkeit bewertet, indem die Veränderung der Schneedecke und der Flussströmungsanomalien mit der Gesamtwasserspeicherung (TWS) von GRACE-Satelliten verglichen wird. Insgesamt zeigt das TWS einen abnehmenden Trend in den von Schnee und Schneeregen dominierten Wassereinzugsgebieten, was unserer Meinung nach auf die schnelle Schneeschmelze bei hohen Temperaturen trotz hoher SF und SWE zurückzuführen ist. Diese Ergebnisse verdeutlichen die wichtigen Veränderungen der kryosphärenhydrologischen Prozesse in der jüngsten Vergangenheit und liefern wertvolle Informationen für das integrierte Wasserressourcenmanagement in Europa.

Task Description

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M.Sc. Geodetic Engineering
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„Identifying Trends in the Temporal Signatures of Snow and its Impact on Catchment Hydrology over Europe during 2000–2022“

for Simran Suresh

Snow is an important component of the hydrological cycle and has a direct impact on surface energy and water balance. Due to its insulation properties, it not only impacts the snow-albedo feedback, thereby the Earth’s energy balance, but also directly contributes to terrestrial water storage (TWS), river flow, and water supply in the snow-dominated regions. Therefore, changes in snow patterns can affect water availability, river flow patterns, and overall catchment water balance.

This thesis aims to understand trends in snow characteristics and their potential impacts on hydrological processes for snow-dominated regions in Europe. The objectives are to (1) identify trends in snow cover fraction (SCF), snow water equivalent (SWE) and river flow for the selected watersheds in the snow dominated regions, and (2) analyze the relationship between TWS anomalies (TWSA) from GRACE and temporal signatures of snow to assess whether there are consistent patterns indicating that changes in snow are influencing total water storage and subsequent river flow variations.

Data sets will include the daily 500 m SCF data from the MODIS satellite (from GlobSnowPack, Dietz et al, 2015) during the period of 2000-2022. SWE data are retrieved from the Global Land Water Storage 2.0 (GLWS2.0) dataset (Gerdener et al, 2023), which is the monthly 0.5. GRACE/GRACE-FO TWSA assimilated into the WaterGAP hydrological model over 2003-2019. These gap-filled data cover the whole European continent and have necessary corrections. In addition, SWE datasets from other sources such as ESA Snow CCI, AMSR-E and CMC will be used for comparison. Meteorological variables like temperature, solid and liquid precipitation from E-OBS dataset are used to analyze on various spatial scales. GRDC river discharge data are used for finding changes in river flow magnitude and shifts. In-situ observations of snow depth from MeteoFrance and MeteoSwiss are also used for validation. The tasks include re-griding to the region of interest, covering the EU continent. SCF and SWE are then resampled to a spatial resolution of 3 km using a nearest neighbor interpolation technique using Climate Data Operator (CDO) tool. Anomalies are computed using the mean of the time series available.

The following analysis will be used to quantify the relationship between snowpack characteristics, TWS, and river discharge for watersheds selected in the thesis:

- Trends in snow signatures: Analysis of the trends will be performed for snow signatures such as snow cover duration, annual maximum SWE and snowfall fraction (ratio of snowfall to total precipitation) in addition to changes in air temperature and precipitation amount.
- Analyze river flow anomalies: River flow anomalies will be calculated using a baseline period or long-term average of the observed river flow. This will provide information on deviations from normal flow conditions.
- Compare the anomalies: In this step, we will analyze the temporal patterns and spatial distributions of TWS anomalies, SCF/SWE anomalies, and river flow anomalies to identify similarities, time lags, or correlations between the analyzed variables.
- Validate with other data sources: This will include cross-validation of the above findings using additional sources of information, such as in-situ measurements of snow depth and snow density, or other satellite observations if available. This will help strengthen the reliability of the observed relationships.

Anticipated results are that positive anomalies in SWE trends must be seen in winter and negative anomalies during spring and summer. These observed patterns will be validated with river gauge discharge data from the GRDC database in mountainous catchments where accumulation relies on solid precipitation. Discharge levels are expected to be lower during winter and higher during spring and summer. Changes in observed patterns of snowpack will provide evidence of shifting precipitation patterns, altered snowmelt timing, and changes in the overall water availability in regions dependent on snowmelt runoff.

The thesis will be conducted at FZ Jülich and will be co-supervised by Dr. Bibi S. Naz.

(J. Kusche)

Contents

1 Introduction

1.1 Motivation

Research studies show that the 21st century is facing a depletion of solid precipitation due to global warming, leading to climate crises and natural hazards in several regions of the world (Gobiet et al 2014). Snow greatly impacts the lives of people and tourism in alpine regions. It is the highly variable component of the cryosphere on both spatial and seasonal scales. Furthermore, it acts as an insulator to the Earth's surface reflecting any heat on it, due to its albedo properties. This indirectly affects the Earth's radiation budget too. These reasons convince us to study the snow accurately in different aspects and draw conclusions on its interactions with other Earth system components like atmosphere, and hydrosphere to name a few.

From a hydrological perspective, studying snow in alpine regions is critical since snow is the main contributor to hydrology. Snow hydrology addresses accurate hydrological forecasting by estimating the timing and amount of water from melting snow that contributes to catchment runoff. Accumulation of winter precipitation in snow cover over several months and its release during the spring snowmelt in a comparatively much shorter time is an important phenomenon (Holko et al 2011). This is critical for water resource management and the production of electricity.

Very few studies highlight the trends of many snow variables together and find the interlinks between each other (Holko et al 2011). Some studies consider one variable such as Snow Water Equivalent (SWE) and evaluate the Total Water Storage (TWS) and water availability in regions like Central Europe, Mountain Asia, and Northeast China. (Notarnicola et al 2020, An et al 2020). There is little importance given to long-term trends of multiple snow variables on a continental scale, which is the motivation and focus of this thesis work.

1.2 Objectives and Literature Review

The thesis aims to address long-term trend analysis of snow variables like snowfall fraction (SFF), snow cover duration (SCD), and snow water equivalent (SWE) and investigates the interconnections with meteorological and discharge data. This study focuses on the whole European continent on a 3 km resolution scale while throwing light on specific watersheds that have needed the most attention in the past few decades. Since a minimum of 3 decades is necessary for trend studies, the study also shows that the period 2000-2022 is sufficient to conclude water availability in the major watersheds of Europe.

The objective of the thesis is to first classify the watersheds in Europe into snow-dominated and snow-rain-dominated based on a temperature threshold. Mann-Kendall tests (Mann 1948, Kendall 1975) are used to find trends and patterns for each watershed. Variables considered here are temperature, precipitation segregated as snowfall and rainfall, snow cover duration, and snow water equivalent. Furthermore, trends in TWS anomalies and river discharges are also computed. A parameter “Center of Timing” (CT, Stewart et al 2005) is computed to measure days taken for half of the total annual river discharge to occur. This parameter is crucial to relate to the snow cover duration. The second objective is to find relationships between the variables. The final objective is to address the water availability of a few watersheds. Also, the results are validated with in-situ measurements from MeteoFrance.

Between 2000 and 2022, advanced snow measurement techniques have surpassed traditional measurement methods. The remote sensing satellites provide higher spatio-temporal coverage that is suitable for snow monitoring, due to its sensitive and regional changes. Furthermore, advances in in-situ measurements have also paved the way for accurate recording of snow variables. These are not limited to snow lysimeters, used when air temperatures are negative, terrestrial laser scanning used in extremely steep terrains, superconducting gravimetry deployed at alpine sites with high gravity sensitivity due to long snow periods, and satellite radars when 1 km spatial resolution is required (Sommer et al 2015, Krajčí et al 2016, Voigt et al 2021, Lievens et al 2019). The interesting and attractive part is that specific instruments are deployed to capture regional snow variability, considering the exact conditions of the region. Thus this literature that focuses on the retrieval methods convinces us that data collected during this period give accurate recordings of precipitation and snow variables.

Snow is sensitive to temperature and precipitation, which are the drivers of snowfall and snowmelt events. Therefore, the use of meteorological variables to conclude changes in snowpack variables is essential. With a warming climate, there are irregular and non-uniform shifts in the snowmelt, runoff, and precipitation patterns. We need large datasets with good coverage and temporal resolution to study the long-term patterns of these variables.

Due to reduced datasets available, there are only a few SWE trend studies focused on the European Alps, which show that for the period 1981–2010, large-scale gridded SWE datasets showed weak nonsignificant decreases, in contrast to the mostly negative SWE trends in the Northern Hemisphere (Mudryk et al 2015). Few studies analyzed decades-long SWE trends in Switzerland, finding no trends in the Swiss Alps for the period 1975–1992 (Rohrer et al 1994) and, differently, pointing out a general reduction of SWE in the last six decades (Marty et al 2017). Only one study was performed in the Central Italian Alps (Bocchiola et al 2009), finding that spring SWE decreased between 1965 and 2007. A recent study of SWE trends in Central

Europe (Colombo et al 2022) indicated increasing air temperature to be the main driver of snow mass loss.

The medium-resolution imaging sensor (MODIS) launched in 2000, gives a long record of snow cover extent (SCE) data which can be used for trend analysis. The study shows there is a negative trend in snow cover duration (SCD) across the Northern Hemisphere with alarming regional changes (Roessler et al 2022).

A joint trend analysis using a multitude of variables including SCD and SWE, along with TWS using the recent datasets developed using advanced retrieval mechanisms with coarser and daily resolution would contribute insightful results about the water availability and catchment hydrology of critical watersheds in the past two decades.

Thus the objectives of this thesis are to consider the association of different variables of snow with discharge and derive the recent trends during the period 2000-2022. The datasets used comprise only remote sensing observations as well as land surface model assimilated simulations.

1.3 Organization of the report

Chapter 2 of the report explains the different datasets used and the post-processing techniques. Chapter 3 outlines the trend analysis technique employed, along with the results of trends for each variable. It also includes the significant relationships found between variables. Chapter 4 considers CT, SWE anomalies, and river flow anomalies and compares them with TWS anomalies. It explains water availability changes in some watersheds in Central and Nordic Europe. Finally, chapter 5 validates the results with an in-situ dataset from a MeteoFrance station and concludes the work.

2 Datasets and Processing

2.1 E-OBS Meteorological Data

The E-OBS data provided by the European Climate Assessment and Dataset (ECA&D) and Copernicus Climate Change Service is available as an open access meteorological dataset. The version used in this study is 27.0e (Cornes et al 2018). E-OBS provides an ensemble dataset on a 0.1^0 regular grid for daily mean temperature *tg*, and daily precipitation sum *rr*. They include a coverage of the European continent 25^0 N - 71.5^0 N x 25^0 W - 45^0 E during the period 1950-01-01 and 2022-12-31, of which data from 2000-01-01 to 2022-12-31 is used for analysis. The data files are in the NetCDF-4 format.

The ensemble dataset is generated via a conditional simulation procedure based on ground-based in-situ observations, encompassing over 3700 stations for temperature and 9000 stations for precipitation across Europe. Each element, including daily temperature (in Celsius) and precipitation (in mm), is represented by a 100-member ensemble. For each ensemble member, a spatially correlated random field is generated using a pre-calculated spatial correlation function. The mean across members yields the best-guess fields, while the spread is determined as the difference between the 5th and 95th percentiles over the ensemble, providing a measure of the 90% uncertainty range.

The mean temperature *tg* taken for this study has the least root mean square error (RMSE) of less than 1.5^0 Celsius and is considered to be the best temperature variable for trend analysis. Precipitation sum *rr* refers to the sum of both snowfall (solid precipitation) and rainfall (liquid precipitation) amounts which has a least RMSE of 3.75 mm which is better compared to other datasets.

2.2 GlobalSnowPack Snow Cover Data

The Global SnowPack is a global snow cover data provided by the German Aerospace Center's Earth Observation Center (EOC). It provides daily Snow Cover Extent (SCE), a 500 m resolution global mosaic derived from interpolated Moderate Resolution Imaging Spectroradiometer (MODIS) snow information of the Platforms Terra (MOD10A1) and Aqua (MYD10A1). This resolution allows for applications in the sub-catchment scale. A series of different processing steps remove the disruptive effect of polar night and cloud cover. The spatiotemporal gaps are filled by a sequence of daily, three-day, topographic, and seasonal interpolations (Dietz et al 2015). This dataset is taken as it provides a long time series data of MODIS snow cover with gap-fillings and corrections.

The data set is available as 8-bit Cloud Optimized GeoTIFF (COG) in the WGS84 projection (EPSG:4326). The individual bit positions indicate whether the pixel is classified as snow or not. A threshold of 64 is set for the snow-covered land. In other words, a pixel value S_i of at least 64 is considered snow-covered (binary 1) and less than 64 as snow-free (binary 0) for each day *i* out of *n* days in a hydrological year. Furthermore, from this information, a parameter Snow Cover Duration (*SCD*) is computed in the unit of days without any normalization, which indicates the summation of all days *i* when each pixel is covered by snow during a certain period *n*. The hydrological year is from October 1 to September 30 of the next year for Europe. For example, the European hydrological year 2001 begins on October 1, 2000, and ends on September 30, 2001.

$$SCD = \sum_{i=0}^{n} Si \quad (1)$$

From 2000 to 2022, the SCD is computed by summing the number of days with binary 1 or snow-covered (Roessler et al 2022). Additionally, SCD is calculated for the winter and spring seasons, which is important for accessing snowfall, snowmelt, and discharge patterns. The post-processing steps of this dataset are specified in the section 2.6.

2.3 GLOBSNOW Snow Water Equivalent Data

The snow water equivalent (SWE) describes the amount of liquid water in the snowpack that would be formed if the snowpack was completely melted. It is also computed by the product of snow depth and snow density. The GlobSnow SWE product set version 2.0, created by the European Space Agency's association represents information on snow water equivalent retrieved from several microwave radiometer satellites - Scanning Multi-channel Microwave Radiometer (SMMR), Special Sensor Microwave Imager (SSM/I) and the Special Sensor Microwave Imager/Sounder (SSMIS) sensors combined with ground-based weather station data from 1979 until 2018 using data assimilation schemes (Luojus et al 2020).

The SWE retrieval and melt detection algorithms are combined to produce snow water equivalent maps (in units of mm) incorporated with information on the extent of snow cover at a spatial resolution of approximately 25 km. SWE of 0 mm denotes snow-free areas (Snow Extent 0%), SWE of 0.001 mm denote areas with melting snow (Snow Extent between 0% - 100%) and SWE of more than 0.001 mm denote areas with full snow cover (Snow Extent 100%).

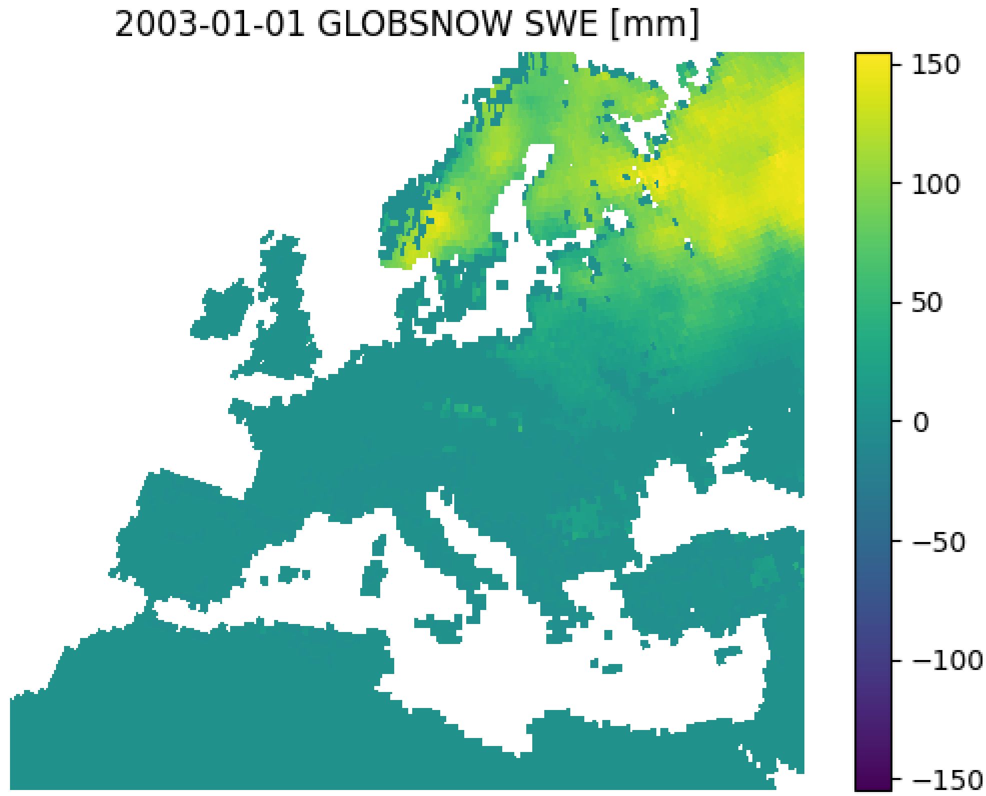


Figure 1: GlobSnow daily SWE estimate as of 1 January 2003

The SWE record is produced on a daily, weekly, and monthly basis, of which the daily data from 2000-2022 is used for the study. Means of SWE during winter and spring are also considered for seasonal trend analysis. SWE information is provided for terrestrial non-mountainous regions of the Northern Hemisphere between latitudes 35N and 85N, excluding glaciers and Greenland. The SWE products are provided in NetCDF format. Thematic accuracy of ~30-35 mm for conditions with less than 150 mm of SWE has been determined for the GlobSnow SWE product (Luojus et al 2011). This dataset is frequently used for SWE analysis, since it combines different microwave sensors with ground station data to achieve improved accuracy. See Figure 1 for a sample of daily SWE data from GlobSnow as on January 1st 2003. The post-processing steps are specified in the section 2.6.

2.4 GLWS2.0 Snow and Total Water Storage Data

Total Water Storage (TWS) is the sum of all above and below surface water storage, including canopy water, rivers and lakes, snow, soil moisture, and groundwater, and it represents the dynamic nature of hydrological quantities. The Global Land Water Storage 2.0 (GLWS2.0) dataset released by the Astronomical, Physical, and Mathematical Geodesy group (Gerdener, Kusche et al 2023) of the University of Bonn, provides monthly TWS anomalies and only snow components at a spatial resolution of 0.5° grids from 2003 to 2019.

Observations from the Gravity Recovery and Climate Experiment (GRACE/FO) mission and its follow-on satellites are assimilated together with a hydrological model WaterGAP. The dataset is gap-filled and includes all necessary corrections. Information about the uncertainty is also included (Gerdener, Kusche et al 2023). The TWS estimates (in units of mm) are used to compute the anomaly from the climatological reference period (2002-2022), and it is updated monthly, with a latency of about 45 days. The snow component from this dataset represents the snow included in the TWS. The well-tested dataset from diverse sensors like geodetic satellites are used for experimenting with the trend analysis. Figure 2 shows the GLWS2.0 monthly snow data in mm on January 2003 on a log scale to view better variability. The post-processing steps are specified in the section 2.6.

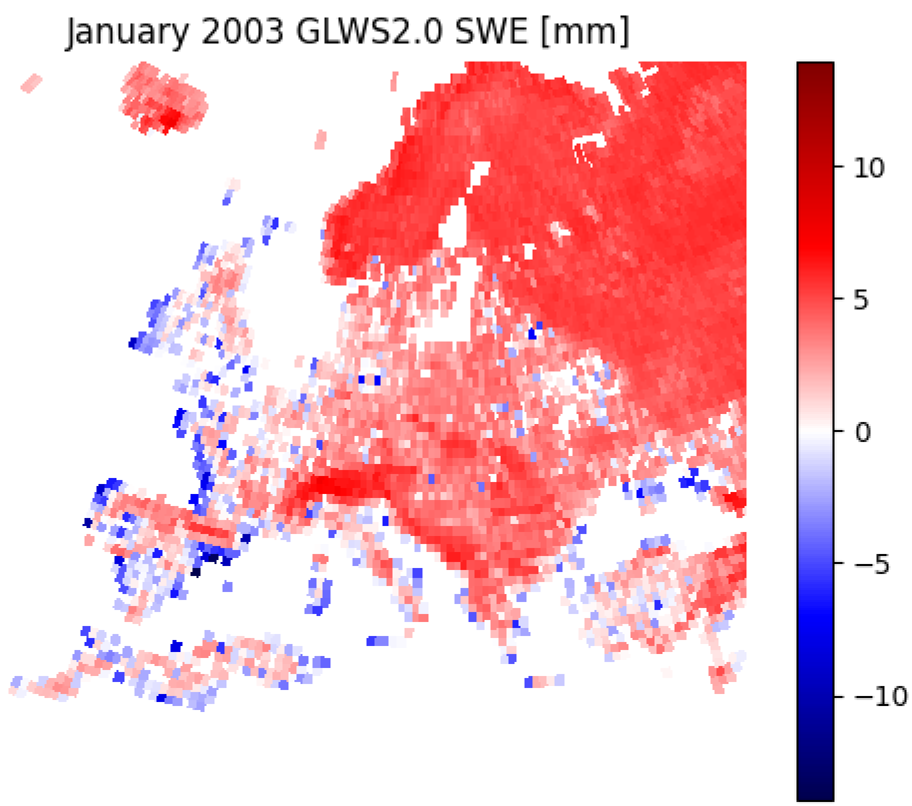


Figure 2: GLWS2.0 monthly Snow data in mm as on January 2003 on a log scale

2.5 GRDC river discharge data

River discharge is the volume of water flowing through a river channel, measured at any given point in cubic meters per second. The Global Runoff Data Center (GRDC) provides daily river discharge data from in-situ measurements of river gauge stations located at various rivers of the world. This rich information is crucial in studying river hydrology. In snow basins, the primary contributors to the river discharge is snowmelt and runoff.

For the European continent, 862 GRDC stations time series are taken that have continuous data from 2000 to 2022. The data is in the format of coordinate information of the GRDC station along with its daily mean discharge time series as the third dimension [latitude, longitude, discharge] which is widely used in literature and easy to use.

The GRDC also provides shapefiles of a particular in-situ station and its contributed area. In other words, there are many river gauges located across the Danube River that measure the river's discharge value. Each GRDC station has a shapefile with an area in which the river discharges. Figure 3 shows the shapefiles provided by GRDC within the European continent and its long-term average discharge value. The long-term average is computed for each station shapefile based on the time series data available for that station. GRDC Long-term statistics are only provided for stations with time series reflecting years of at least 10 months, and months of at least 20 days for the available daily discharge data for each station.

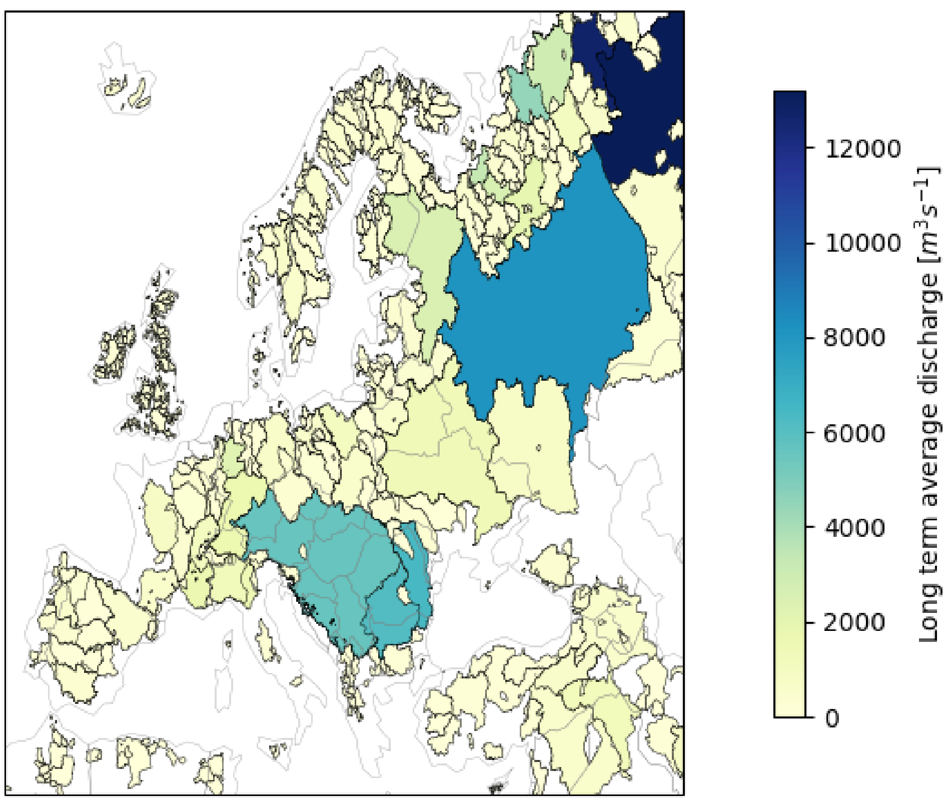


Figure 3: Long-term average discharge values for each GRDC station shapefile based on the time series available for that station.

2.6 Processing of Datasets

The original datasets are first downsampled to a finer resolution. This is accomplished to make all datasets consistent in horizontal resolution for trend analysis. This applies only to GlobalSnowpack snow cover (500 m resolution), GLOBSNOW SWE (25 km resolution), and GLWS2.0 SWE (50 km resolution) products. E-OBS has a finer resolution of 0.1^0 and GRDC discharge is station-based and not grid based. Nextly to compute the individual trend analysis for each watershed, a spatio-temporal mean of each variable for each watershed is required.

1. The SCD dataset from Global SnowPack and SWE datasets from GLOBSNOW and GLWS2.0, along with its TWS anomaly data are reprojected to the EU-CORDEX (European Coordinated Regional Climate Downscaling Experiment) for European domain at 0.0275 deg (~3 Km), which comprises the boundaries -49.7ºW, 70.6ºN, 74.6ºE, 19.9ºS. This is accomplished using the GDAL *gdaltransform* operator (Quin et al 2020). This operator involves a scale change in source projection to the UTM projection.

2. This data is then resampled to a 0.0275^0 (~3 Km) resolution grid using the "*conserve*" *interpolation* mode from the NCAR Command Language (NCL, 2012). This interpolation types preserves the adjacent pixels to a subgroup and smoothes the surrounding pixels.

3. All the datasets are processed to get the annual, winter, and sping mean for each year during the period 2000-2022. This is computed using the Climate Data Operator (CDO 2023) *yearmean* and *seasmean* commands. Annual mean is computed using the *yearmean operator.* Winter months include December, January, and February and spring months include March, April, and May and are computed using *seasmean* operator.

4. Snowfall fraction is the amount of precipitation that falls as snow, referred to as solid precipitation, and is required for the classification of snow-dominated, snow-rain-dominated, and rain-dominated watersheds. E-OBS daily temperature and precipitation data are used. Using a simple precipitation partition method, the snowfall and rainfall can be computed. The minimum temperature for rain to occur ($T_{RAINMIN}$) and maximum temperature for snow to occur ($T_{SNOWMAX}$) are set to 0^o and 2^o Celsius respectively. When the temperature $T <= T_{RAINMIN}$, there is a 100% probability of snowfall to occur, and when $T >= T_{SNOWMAX}$, there is a 100% probability of rainfall. Temperatures between 0 and 2^o C give the snowfall fraction as a linear interpolation between the two values. In other words, precipitation at 0.5^o C temperature would be 75% due to snowfall, and 25% due to rainfall (Bourgault et al 2023). These quantities constitute the snowfall fraction (SFF) and rainfall fraction (RFF). When multiplied with the precipitation sum, gives snowfall (SF) and rainfall (RF) amounts respectively (in mm units).

5. Lastly, the processing of all the meteorological variables - Temperature T, Precipitation P, SF, RF, snow variables - SCD, SWE, TWSA, and discharge variables are computed for each station by masking the shapefile of the station from the gridded daily data for annual, winter, and spring periods. A spatial mean of the station's grid gives a time series in annual, winter, and spring scales for each station. This data can be used for the trend analysis, which is in the format of [WID, 2000, 2001,…,2022], where WID is the GRDC station number and 2000…2022 represents the watershed's yearly, winter, and spring spatiotemporal mean for each quantity.

2.7 Classification of snow-dominated watersheds

From the European GRDC stations selected within the boundary, classification of snow-dominated, and snow-rain-dominated watersheds is required. The snowfall fraction (SFF) estimates are considered for this purpose.

Berghuijs et al 2014 have shown that stratified long-term mean snow fraction and streamflow measurements in a range of catchments during the warming climate prove to be useful for determining precipitation shifts of snow towards rain. Using similar approach as Berghujis et al 2014, a SFF threshold of 0.15 is chosen for the partition of snowfall and rainfall dominance in precipitation patterns. Therefore watersheds with SFF between 0.15 and 1 or those that receive more than 15% solid precipitation are classified as snow-dominated (SD). Similarly, watersheds with SFF between 0.05 and 0.15 or those where 5-15% of precipitation falls as snow are both snow- and rain-dominated stations (SRD).

Long-term mean temperature, precipitation, and snowfall fraction data processed from section 2.6 are used. The period from 1950-2022 is used for long-term mean analysis along with the trend analysis period 2000-2022. Table 1 shows the number of GRDC stations classified as SD and SRD during these periods from a total of 1670 GRDC stations.

Table 1: Classification of snow-dominated (SD) and snow-rain-dominated (SRD) GRDC stations based on the long-term mean of two periods 1950-2022 and 2000-2022

Long-term period considered	SD	SRD
1950-2022	644	277
2000-2022	580	282

It can be seen that there are very less changes in the number of stations categorized as snow-dominated and snow-rain-dominated watersheds during the two long-term periods considered. Thus for the thesis, classification using the data from period 2000-2022 is sufficient to study long-term patterns. There is an evident decrease in SD stations and a few stations are increasingly categorized as SRD compared to two periods, which can be attributed to the fact that precipitation patterns in recent decades have shifted from snowfall to rainfall as shown by Berghuijs et al, 2014.

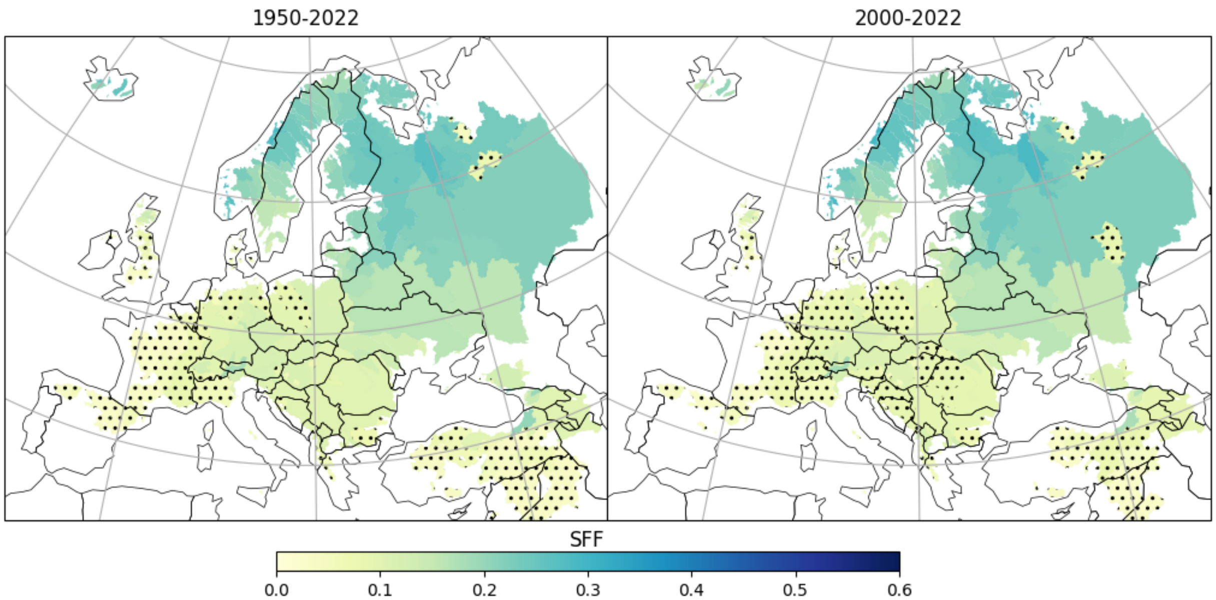


Figure 4: Spatial plot of Snowfall fraction of GRDC stations computed by the long-term mean of 1950-2022 and 2000-2022.

Figure 4 shows the spatial plot of snowfall fraction distribution for the selected stations during the long-term mean period of 1950-2022 and 2000-2022. Only SRD stations are indicated by hatch. Many watersheds in Northern and Eastern Europe have the same snowfall fraction during both periods showing minimal snow variability over decades. Some Central European watersheds, especially in the Meditteranean regions have reduced SFF and a few major watersheds like the Rhine, Elbe, and Danube have transitioned from snow-dominated to snow-rain-dominated during the last two decades which are driven by extreme events and anthropogenic forcing.

3 Trend Analysis and Identifying Relationships between the Variables

The first objective of the thesis is to find trends in the variables - Temperature (T), Precipitation (P), Snowfall (SF), Rainfall (RF), Snow cover duration (SCD), Snow water equivalent (SWE), Total water storage anomaly (TWSA), and River discharge during the period 2000-2022. For this, the Mann-Kendall trend test is employed.

3.1 Mann Kendall test

The Mann–Kendall (MK) test (Mann 1948, Kendall 1975) is a non-parametric statistical test used to determine whether there is a monotonic trend in a time series. The Theil–Sen slope (Theil and Sen 1968) is used to determine the magnitude of the trend. In the MK test, the null hypothesis (H_o) indicates no trend, while the alternative hypothesis indicates the presence of a trend. The MK test is one of the simplest and widely used methods for trend analysis.

The MK test works by examining the ranks of data points over time. If i and j stand for two consecutive years (where j is later than i), x_i and x_j stand for the spatio-temporal mean of the variable of the corresponding years. First, the strength of the sequence for the time series is described by the MK statistic S is derived for n number of years using a signum function *sgn*. This gives the sum of amount of difference between two consecutive years.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i)$$

$$sgn(x_j - x_i) = \begin{cases} +1 \ (x_j - x_i > 0) \\ 0 \ (x_j - x_i = 0) \\ -1 \ (x_j - x_i < 0) \end{cases} \tag{2}$$

After that, the variance of S depending on the number of years n is calculated.

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \tag{3}$$

Finally, the Z statistic is calculated from S and $Var(S)$, which states whether there is a positive or negative trend in the time series data based on the hypothesis defined.

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} \ (S > 0) \\ 0 \ (S = 0) \\ \frac{S+1}{\sqrt{Var(S)}} \ (S < 0) \end{cases} \tag{4}$$

The trend is significant when $|Z| \geq Z(1-\alpha/2)$, where α is the significance level corresponding to the p-value and can be set to e.g., 0.05. Finally, the magnitude of the trend (β) is calculated by the Theil–Sen slope given by,

$$\beta = Median\left(\frac{x_j - x_i}{j - i}\right) \tag{5}$$

The MK test is implemented using the Python package *pymannkendall* (Hussain 2019). The ordinary MK test *original_test* is applied to the annual time series and the Modified Seasonal MK test *seasonal_test* is applied to the winter and spring time series of the variables. The execution results are trends seen (increasing/decreasing/no-trend), significance level (p-value), and the Theil–Sen slope value. The results of the trend analysis of the variables are discussed in sections 3.2-3.6.

3.2 Temperature and Precipitation Trends

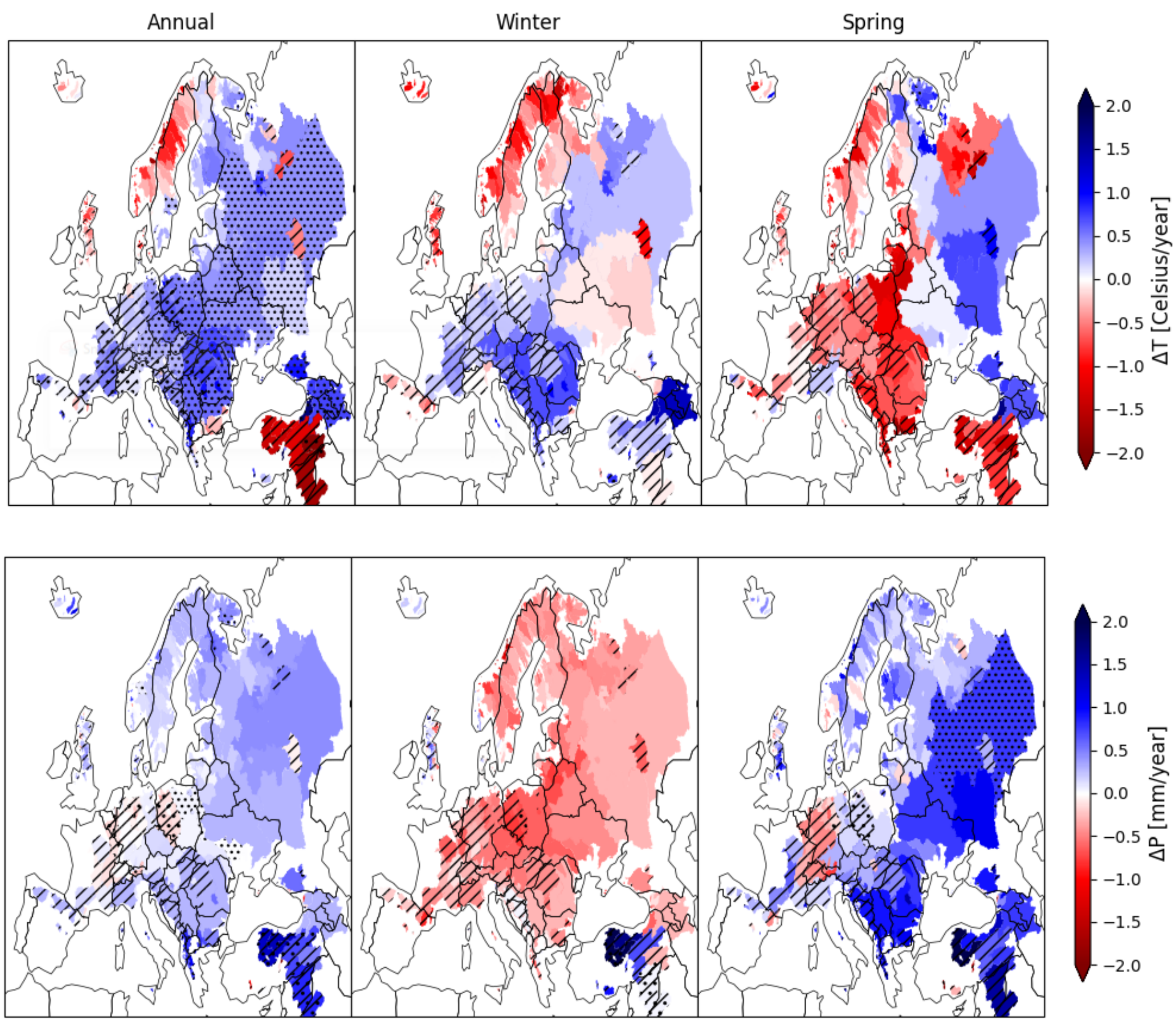


Figure 5: Temperature and Precipitation trend slope value for the GRDC stations during 2000-2022 for the annual, winter (DJF) and spring (MAM) scales. Dot hatched are significant trends $p<0.05$ and line hatched are snow-rain-dominated stations.

Figure 5 shows the slope value or magnitude of the trend for the variables temperature (ΔT in Celsius/year) and precipitation (ΔP in mm/year) during the period 2000-2022 for the annual, winter, and spring timescales. Dot-hatched stations indicate significant trends ($p<0.05$, 95% confidence interval), and line-hatched stations are classified as snow-rain-dominated.

In the annual trends, it can be seen that there is a monotonic increase in both T and P in most Central European watersheds. A major watershed in Southeastern Europe (Volga River), Icelandic, and almost all Scandinavian watersheds experience a inverse trend in T and P.

In the winter trends, there is a negative trend of P and increasing T for the Central European watersheds. Scandinavian watersheds experience a decrease in both T and P. However, no significant trends are seen in this season.

During the spring, a strong inverse trend of T and P is seen for Central and Scandinavian watersheds. A positive correlation is seen in the largest Eastern watersheds as well as those in France, Germany, and Spain. A slight positive trend is seen in the alpine watersheds, particularly the Rhine, Po, and Danube rivers.

In general, the results reveal rising temperature trends across Europe in both the annual and winter seasons. However, during spring, the upward temperature trends are more pronounced in Eastern Europe, while decreasing trends are observed in watersheds within mid-Europe. Similarly, increasing trends in precipitation at the annual scale are identified, but negative trends (decreasing) are more pronounced during the winter season.

Over Europe few recent studies have also found a decreasing trend in precipitation over certain parts of Europe in recent years. For instance, a study by Ionita et al 2020 showed a significant negative trend in the precipitation amount over the last years, particularly in central Europe. They found a reduction of approximately 50% of the usual April rainfall amount over large areas in central Europe during the period from 2007 to 2020. However, a report by the Copernicus Climate Change Service 2018 stated that precipitation over Europe as a whole does not show a significant trend, either for annual or for seasonal values, although there were large spatial differences.

3.3 Snowfall and Rainfall Trends

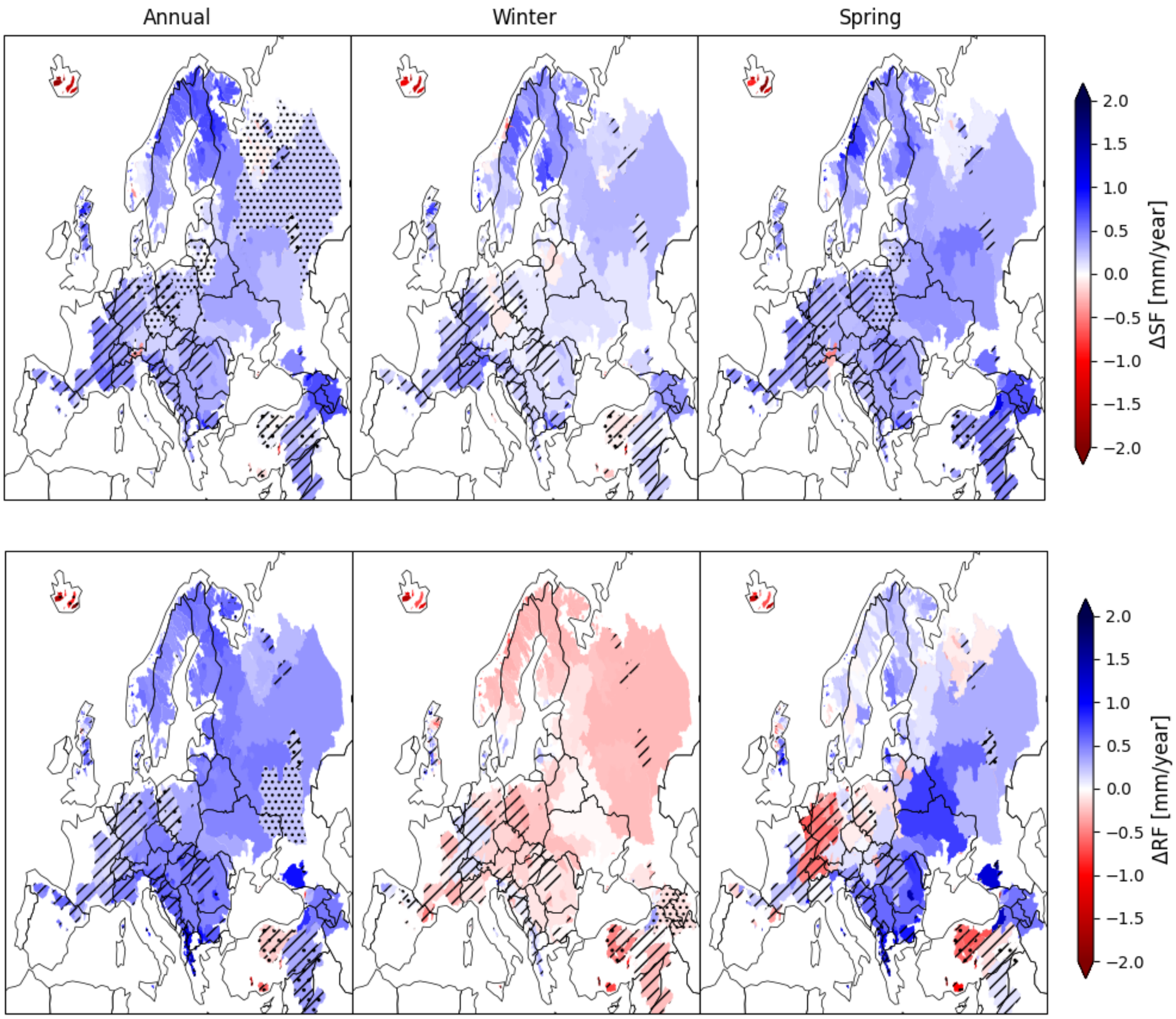


Figure 6: Snowfall and Rainfall trend slope value for the GRDC stations during 2000-2022 for the annual, winter (DJF) and spring (MAM) scales. Dot hatched are significant trends p<0.05 and line hatched are snow-rain-dominated stations.

Figure 6 shows the slope value or magnitude of the trend of the variables snowfall (ΔSF in mm/year) and rainfall (ΔRF in mm/year) during the period 2000-2022 for the annual, winter, and spring timescales. Dot-hatched stations indicate significant trends ($p<0.05$, 95% confidence interval), and line-hatched stations are classified as snow-rain-dominated.

The result of the precipitation partition in Section 2.6 Step 4 gives the snowfall and rainfall amounts in mm. The precipitation sum comprises both snowfall (SF) and rainfall (RF). This implies if P increases, either both SF and RF increase or one variable increases and the other decreases. This can be seen in the winter and spring seasons.

The annual trend shows a monotonic increase in both SF and RF, thereby the precipitation increase (see Figure 5 also). At annual scale, significant trends are seen in Eastern Europe.

In the winters of 2000-2022, snowfall has increased upto 2 mm/year and not significant in the whole of Europe and rainfall has reduced. Snowfall has dominated even in snow-rain-dominated watersheds. Interestingly during the springs, snowfall and rainfall have slightly increasing trends, except in the alpine regions. Alpine and snow-rain-dominated watersheds in Central Europe particularly the Rhine River have a inverse relation of SF with RF. There is not much significance in the trends during the two seasons.

Overall it can be concluded that spring precipitation increase is due to both SF and RF except in the Rhine and Po rivers, where a decrease in precipitation is more influenced by RF than SF.

3.4 Snow Cover Duration and Snow Water Equivalent Trends

Figure 7 shows the slope value or magnitude of the trend of the variables Snow cover duration (ΔSCD in days/year) and Snow water equivalent (ΔSWE in mm/year) of both GLOBSNOW and GLWS2.0 datasets during the period 2000-2022 for the annual, winter, and spring timescales. Dot-hatched stations indicate significant trends ($p<0.05$, 95% confidence interval), and line-hatched stations are classified as snow-rain-dominated.

The snow cover extent (SCE from Global SnowPack) from which the SCD is calculated has decreasing trends in Europe. There is a pronounced decrease in SCD during all timescales across the whole of Europe. Some watersheds like the Volga River basin in the Northeastern range experience an increase in snow days throughout the year. A significant trend is seen overall in all regions. Figure 6 shows a monotonic increase of snowfall in all seasons except the Italian Alps, and Figure 5 shows an overall increase in the temperature, this gives the conclusion that snowmelt happens at a faster pace leading to fewer snow days in a year. Therefore, the overall trend in SCD is decreasing across Europe.

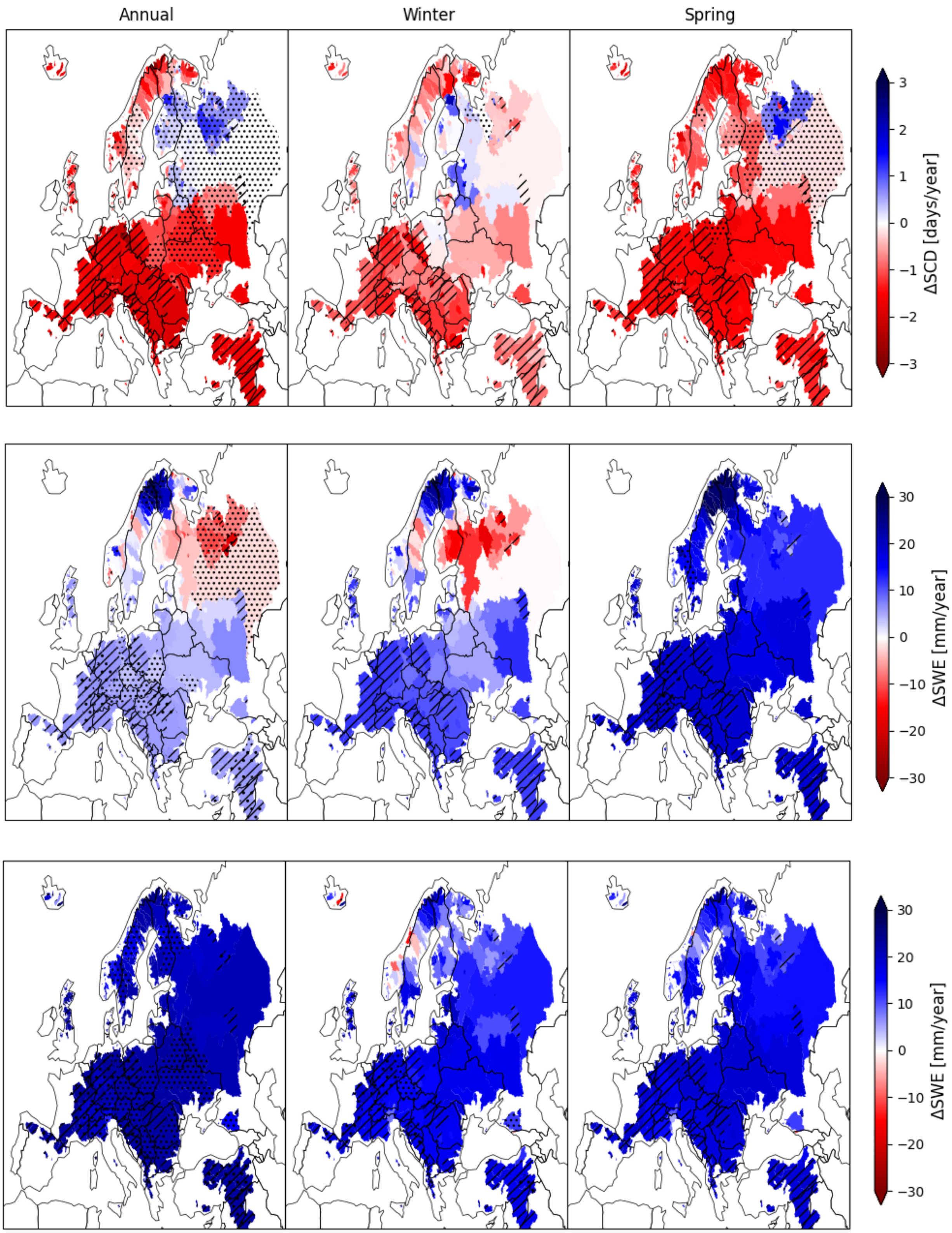


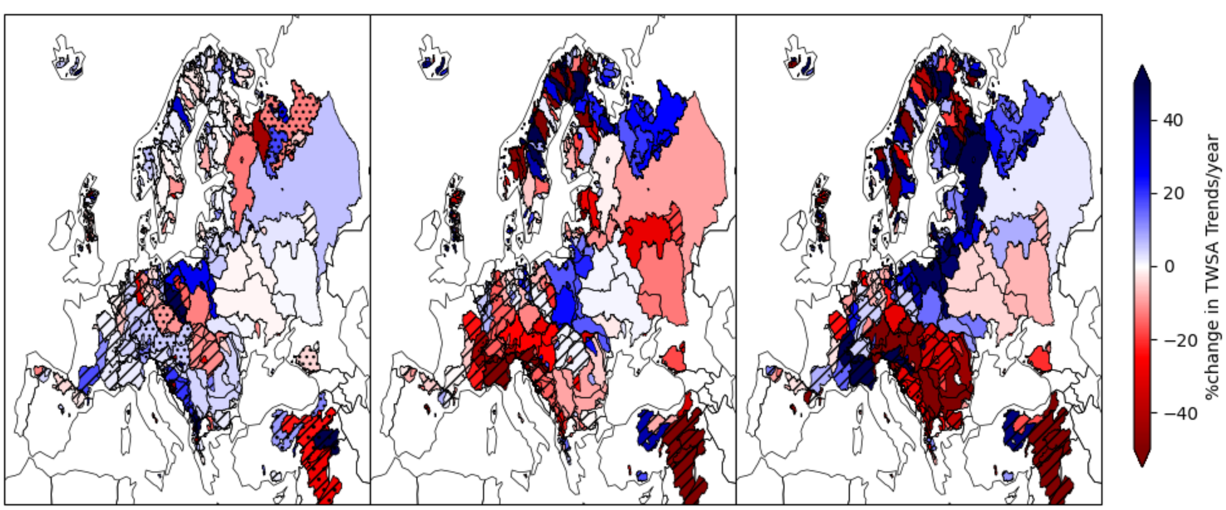
Figure 7: SCD from Global SnowPack and SWE from GLOBSNOW and GLWS2.0 datasets trend slope value for the GRDC stations during 2000-2022 for the annual, winter (DJF) and spring (MAM) scales. Dot hatched are significant trends p<0.05 and line hatched are snow-rain-dominated stations.

SWE datasets are available at a spatial resolution of 25 km and 50 km (0.5°) from GLOBSNOW and GLWS2.0 respectively. The datasets are downscaled to 3 km resolution as shown in Section 2.6. The GLOBSNOW data is observed using microwave radiometer sensors which gives a good regional variability. The GLWS2.0 data retrieved from satellite gravimetry sensors and assimilated into the hydrological model WaterGAP (Gerdener and Kusche et al 2023) gives snow changes due to temporal gravity variations. Also notable is the sampling period. Since the snow has a short lifetime before its rapid melting starts, a monthly resolution given by the snow component of GLWS2.0 makes it hard to study regional and short-scale variations. However, for trend analysis, the monthly dataset GLWS2.0 shows a monotonic increase in SWE, with significant trends observed in the alpine regions. This is consistent with SF trends. Nordic watersheds experience high precipitation levels due to which the SWE has positive trends. This is visible in the GLOBSNOW SWE trends in all seasons as well as in GLWS2.0 SWE trends during winter only. Significant trends are seen in the annual time scale in GLOBSNOW SWE and in the annual and winter time scales in GLWS2.0 SWE for a few Central watersheds.

3.5 Total Water Storage Anomaly and Discharge Trends

Figure 8 shows the percentage change of slope value or magnitude of the trend of the variables Total Water Storage anomaly (ΔTWSA in mm/year) from the GLWS2.0 dataset and the slope of discharge (ΔDISCH in m^3s^{-1}/year) from GRDC during the period 2000-2022 for the annual, winter, and spring timescales. The percentage change is taken for TWSA as it consists of anomalies and is computed by the product of **β** (Theil Sen's slope) and the sampling period divided by the corresponding mean given by (Taxak et al 2014),

$$Percentage\ change\ (\%) = \frac{\beta\ x\ sampling\ period}{mean}\ x\ 100 \qquad (6)$$



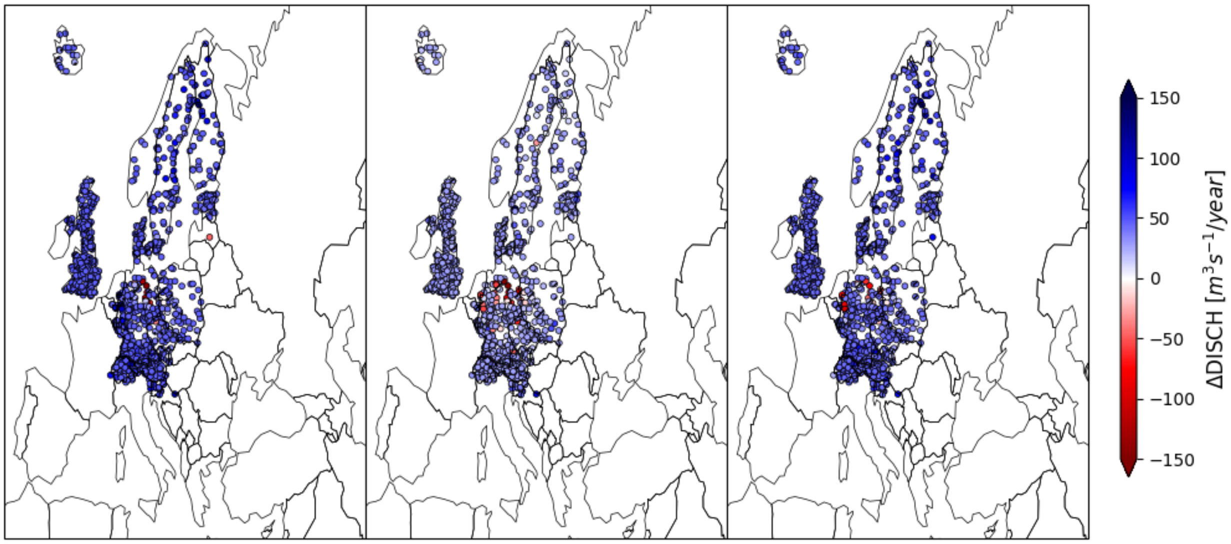


Figure 8: TWSA in percentage change of slope from GLWS2.0 dataset and discharge from GRDC slope value for the GRDC stations during 2000-2022 for the annual, winter (DJF) and spring (MAM) scales. In the first row figure, Dot hatched are significant trends p<0.05 and line hatched are snow-rain-dominated stations.

In the first row figure, GRDC station shapefiles are plotted wherein, dot-hatched stations indicate significant trends (p<0.05, 95% confidence interval), and line-hatched stations are classified as snow-rain-dominated. In the second figure, GRDC station locations with their discharge slope as color codes are plotted.

TWSA trends show negative slopes in the Central snow and snow-rain-dominated watersheds, especially the alpine regions have strongly decreasing trends. The Nordic watersheds experience a mix of both positive and negative trends. The Volga River which is the largest of the watersheds, has a positive trend in spring due to the snowmelt at increasing temperatures. This is consistent with the increase in SF, RF, and SWE and constant SCD throughout the period.

In this analysis, 862 GRDC stations that have continuous daily mean discharge data during the period 2003-2019 are considered. This period is chosen to be consistent with the availability of TWSA data for comparison. Stations in Eastern Europe, Italy, France, and Spain do not have GRDC time series available data during this period. Discharges show a positive trend across Central and Northern Europe. The increase in snowfall and SWE are the reasons for that. Few Central watersheds experience decreasing trends in discharge during all time scales. In general spring season experiences highly positive discharge variations compared to the winter season due to the snowmelt phenomenon. The impact of SCD and SWE on the discharge magnitude and timing is a crucial aspect to address the watershed management.

3.6 Center of Timing Trends

The center of timing (CT) is an important variable in assessing the discharge timing of a watershed. To calculate CT, the hydrological year or water year is taken, which is from October 1 to September 30 of the next year for Europe. For example, the European hydrological year 2001 begins on October 1, 2000, and ends on September 30, 2001. *CT* is defined as the number of days a river or watershed takes to discharge half of its total annual volume (Stewart et al 2005). For each year in the period 2000-2022, CT is computed in days. Mathematically, the center of timing can be expressed as

$$CT = \sum_{t=1}^{n} tq \,/\, \sum_{t=1}^{n} q \tag{7}$$

where *t* is the time from the beginning of the year (water year) (in days) corresponding to *q* upto *n* days in a year, and *q* is the streamflow value in the daily time series approaching *0.5**Q*, where *Q* is annual streamflow by volume, which is summed for each hydrological year.

In the sections 3.7 and 4.3, where CT computed annually is compared with winter and spring seasons, the fraction of CT contributing to the streamflow in that season is computed to assess the seasonal changes. The snowmelt runoff is the largest contribution to annual flow for snowmelt-dominated basins, CT provides a time-integrated perspective of the timing of this phenomenon and the overall distribution of flow for each year, and it is less noisy than its winter and spring counterparts. The trends in CT are linked to the timing of snowmelt using temperature variations and it is significant to study the discharge timing. CT indicates the days of lag of discharge, with positive lag indicating delay and negative lag indicating early shift.

Figure 9 shows the slope value or magnitude of the trend of the variable Center of Timing (CT) (ΔCT in days/year) of the GRDC stations classified as snow-dominated, snow-rain-dominated, and rain-only dominated for the hydrological years 2000-2022.

Central European watersheds experience decreasing trends in CT. The European Alps, the UK, and Iceland experience increasing CT trends. Nordic watersheds have mixed trends, also notable is that they are either snow-only dominated or rain-only dominated.

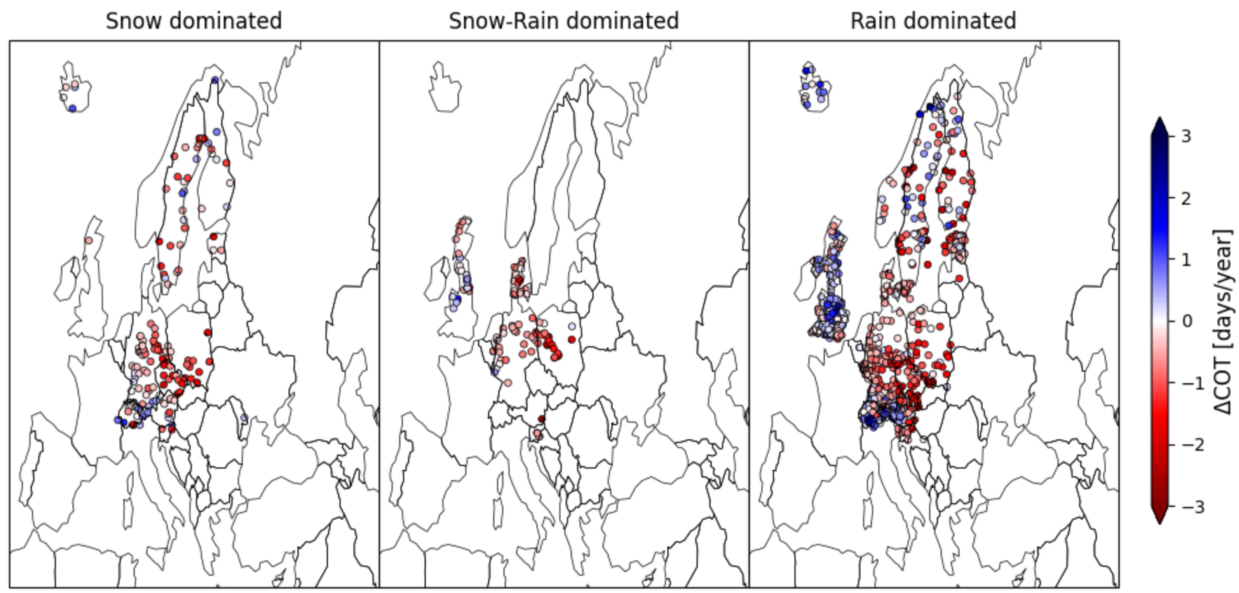


Figure 9: Center of Timing slope value during the hydrological years 2000-2022 for the GRDC stations classified as snow-dominated, snow-rain-dominated, and rain-only dominated. Scatters indicate station location with CT as the color code.

Alpine-fed rivers discharge more due to snowmelt, which implies that the CT trends are increased or delayed due to increasing trends in snowfall and SWE. Central European watersheds have a negative SCD trend which imply less snow covered days and rapid snowmelt due to high temperatures, leading to fast or early discharge (decreased CT). Moreover, in Nordic regions, the year-long snow existence delays the snowmelt and CT. This concludes overall, snow dominated regions have delayed discharge and snow-rain dominated and rain-only dominated regions have early discharge. Notably, snow-dominated watersheds discharge due to snowfall mainly, but rain-dominated watersheds discharge due to both snowfall and rainfall.

As reported by the European State of Climate, Central Europe faced numerous water disasters due to the lower volume of discharge by the major rivers - Elbe, Rhine, Danube, Po, and Rhone. Though harsh snowfall existed during the period 2000-2022, rapid snowmelt events backed by warming temperatures led to a increase in river volume and discharge, thereby causing an early onset of the CT by 2-3 days, thus showing decreasing trends.

3.7 Relationship between variables

In this section, the relationships between different variables established are quantified. The comparison of variables snowfall (SF) with precipitation (P), snow cover duration (SCD) with the center of timing (CT), and snow water equivalent (SWE) with discharge (DISCH) give interesting insights into the intersection of snow variability and associated hydrological effects.

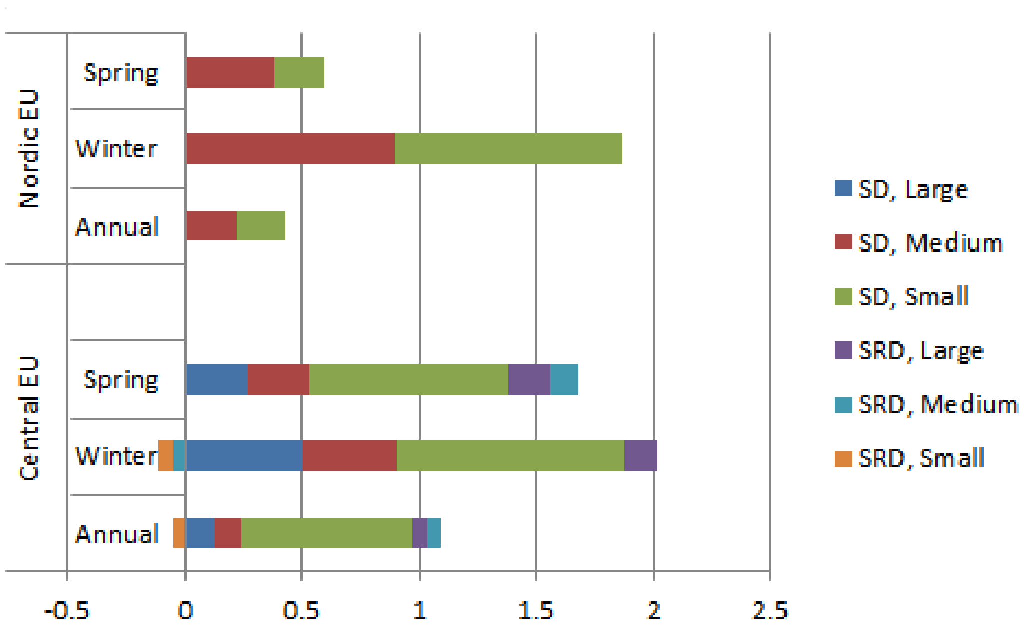
The rivers taken for analysis are shown in Table 2.

Table 2 shows the rivers taken for watershed-based analysis. Large size refers to an area spanning more than 10^0, Medium refers to an area between $1\text{-}10^0$ and small is less than 1^0. No snow-rain-dominated watersheds and large snow-dominated watersheds are found in Nordic Europe (marked as -).

Region	Snow dominated			Snow-rain dominated		
Area	**Large**	**Medium**	**Small**	**Large**	**Medium**	**Small**
Central EU	Danube	Rhine	Rhone	Rhine	Weser	Gudena
Nordic EU	-	Ljusnan	Indal	-	-	-

3.7.1 SF vs P

The bar plot in Figure 10 shows the linear regression slope using a polynomial fit of degree 1 for the seasonal time series (Annual, winter, and spring) of the snowfall and precipitation variables for the watersheds given in Table 2. Nordic SD rivers include Ljusnan and Indal. A highly positive regression slope is seen in both watersheds, especially during the winter. Snow-dominated watersheds mean snowfall dominates the precipitation, which proves the high positive correlation between the two variables.



Regression slope

Figure 10: Regression slope of seasonal time series of snowfall and precipitation of watersheds in Central Europe and Nordic Europe.

In Central Europe, the snow-dominated watersheds, especially smaller (Rhone) and medium (Rhine) river GRDC stations that have an area of less than 1^0 and $1\text{-}10^0$ show a significant positive change. Large watersheds with an area of more than 10^0 experience both solid and liquid precipitation, thereby having a smaller slope.

3.7.2 SCD vs CT

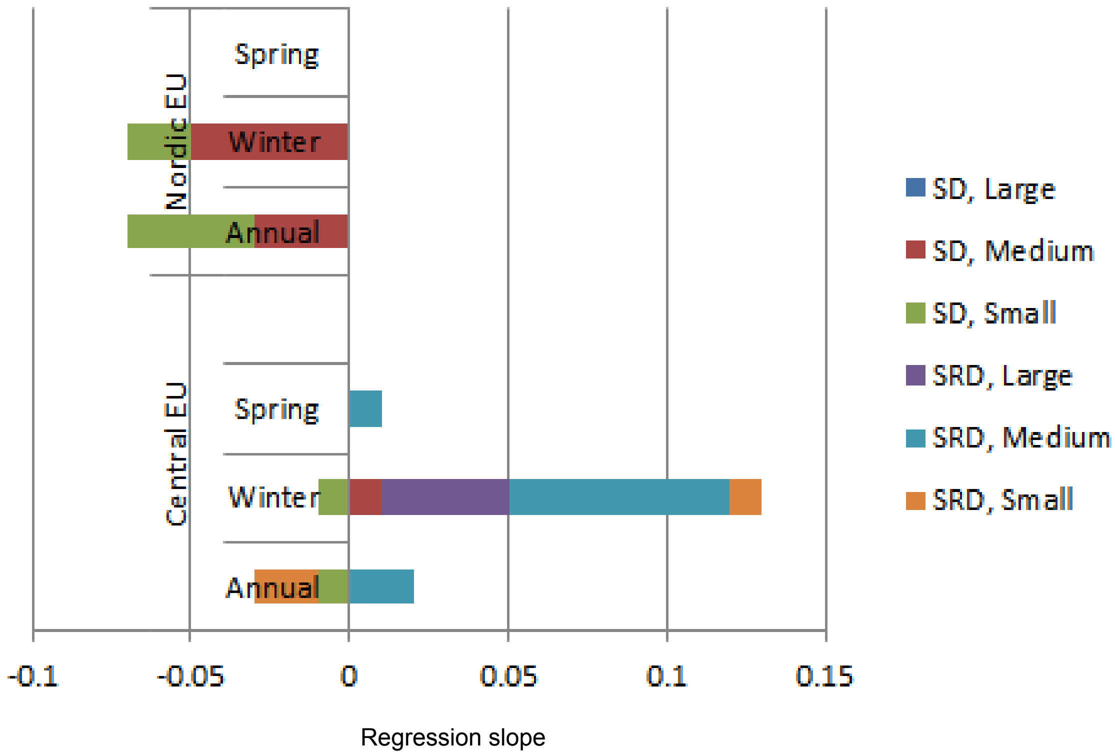


Figure 11: Regression slope of seasonal time series of snow cover duration and Center of the timing of watersheds in Central Europe and Nordic Europe.

The bar plot in Figure 11 shows the linear regression slope for the seasonal time series (Annual, winter, and spring) of the snow cover duration (SCD) and center of timing (CT) variables for the watersheds given in Table 2.

There is no relation between the area of the river and the regression of its SCD and CT. Clearly, Nordic rivers show a negative slope which implies more snow days or SCD lead to early discharge or CT. In these regions, temperature has a positive correlation with precipitation (see Figure 5) where increasing temperature does not decrease precipitation but affects snowmelt during winters. Though the temperature decreases in Northern regions, snow stays throughout the winter or even yearlong and its constant snowmelt-runoff phenomenon makes the CT shift earlier. In other words, rivers discharge their annual volume quicker due to rapid snow accumulation and melt.

Most rivers in Central EU show a positive slope in the winter. From Figure 5 and 7, the temperatures are increasing and SCD is decreasing in these regions, which imply rapid melting and fewer snow days. This snowmelt will cause the river to discharge faster, and achieve the annual streamflow earlier. Thus less SCD and early CT cause a positive slope. This is more pronounced in winter and for snow-rain-dominated rivers (Rhine and Weser) which discharge both solid (snowmelt) and liquid precipitation (rainfall).

3.7.3 SWE vs CT

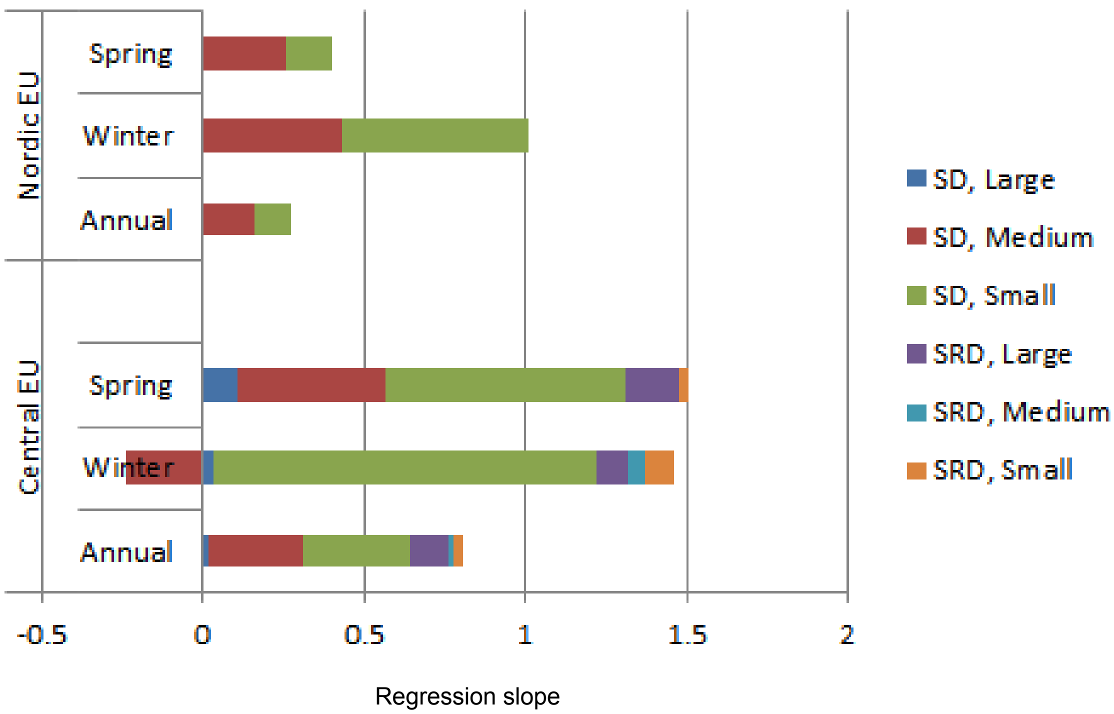


Figure 12: Regression slope of seasonal time series of snow water equivalent and Center of the timing of watersheds in Central Europe and Nordic Europe.

The bar plot in Figure 12 shows the linear regression slope for the seasonal time series (Annual, winter, and spring) of the snow water equivalent (SWE) and center of timing (CT) variables for the watersheds given in Table 2.

Smaller and medium snow-dominated watersheds have a stronger impact of the SWE on its center of timing in both Nordic and Central rivers. As snowfall increases (see Figure 6), the SWE also increases thereby discharging more volume. This higher annual streamflow volume will take longer to discharge, which delays the CT. This explains the fact that SWE has a positive relationship with CT.

An exception is the Rhine River GRDC station 6335170, which is classified as medium snow-dominated. Rottler et al 2021 show that the Rhine basin flowing from this station area

(Northern Alps) to the Basel region experiences heavy snowmelt, due to rising temperatures and increases streamflow conditions, leading to flooding threats. This is useful to conclude that high SWE causes rapid streamflow and early CT, thereby a negative relation between the two variables for this region.

3.7.4 SWE vs TWSA

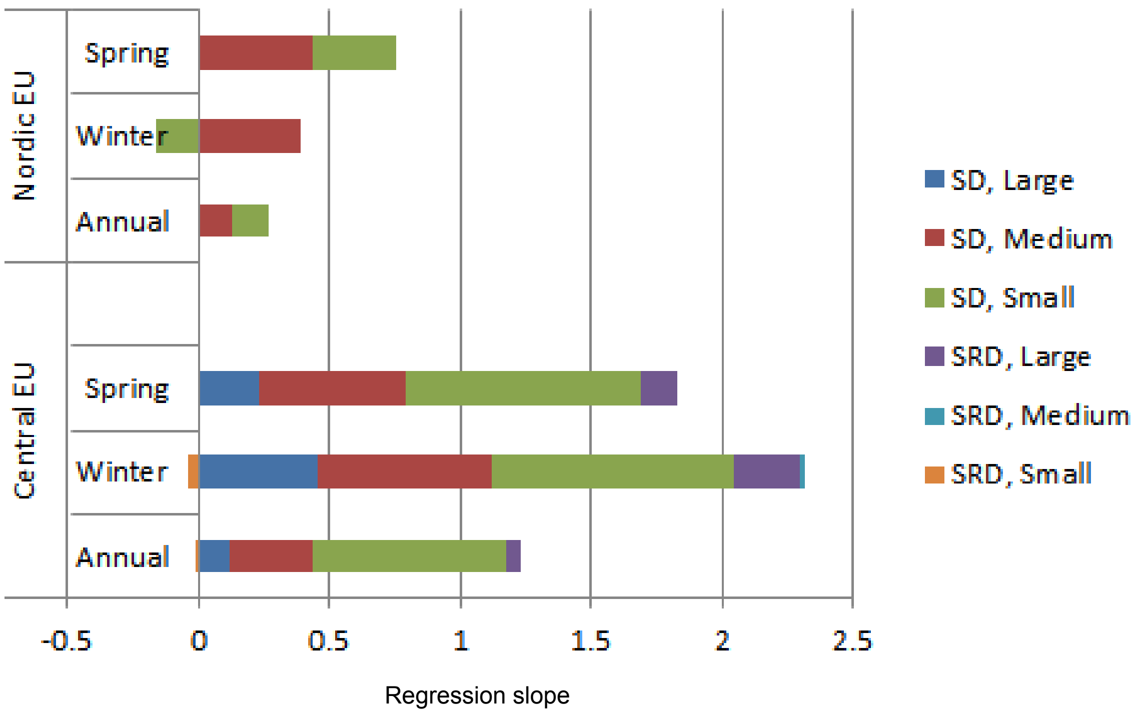


Figure 13: Regression slope of seasonal time series of snow water equivalent and total water storage anomaly of watersheds in Central Europe and Nordic Europe.

The bar plot in Figure 13 shows the linear regression slope for the seasonal time series (Annual, winter, and spring) of the snow water equivalent (SWE) and total water storage anomaly (TWSA) variables for the watersheds given in Table 2.

A very highly positive relationship is observed between the SWE and TWSA. From Figure 7, there is a monotonic increase in SWE observed from varied instruments (microwave and gravimetric sensors) across the continent. In winter, some Northeastern rivers show a negative trend.

In the rivers taken for analysis, snow-dominated ones show a highly positive relationship between SWE and TWSA. An increase in SWE can be explained by an increase in snowfall. Thus it is valid that snow-rain-dominated watersheds have a lesser impact. The area also plays a major role as medium and small-size watersheds contribute more to the TWSA variability.

In Figure 8, TWSA shows a steady decline in Central Europe and Nordic rivers have a mix of TWSA variability. Interestingly, the SWE increase cannot compensate for the TWSA decrease though there is a positive correlation. In other words, even though SWE has higher weightage in the TWS at snow-dominated regions, other components like soil moisture, groundwater, canopy, and surface water have depleted to a greater extent such that SWE has very little contribution to increase the TWSA trends.

3.7.5 SWE vs Discharge

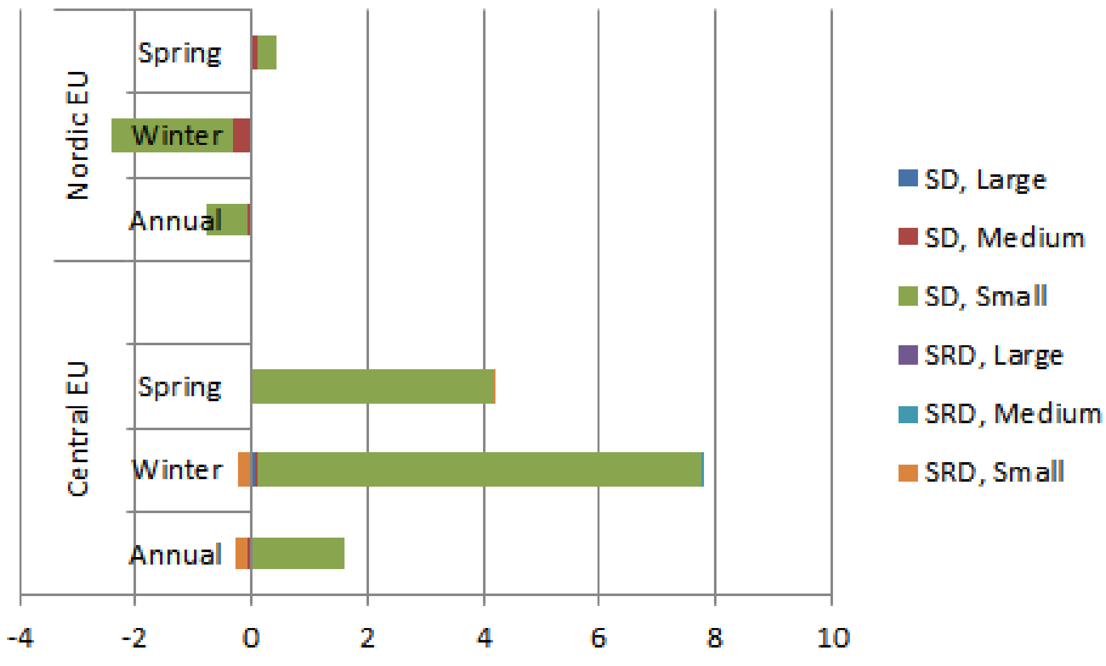


Figure 14: Regression slope of seasonal time series of snow water equivalent and discharges of watersheds in Central Europe and Nordic Europe.

The bar plot in Figure 14 shows the linear regression slope for the seasonal time series (Annual, winter, and spring) of the snow water equivalent (SWE) and discharge variables for the watersheds given in Table 2.

Highly significant effects of this relation are seen in smaller snow-dominated watersheds. In Central Europe, the increase in SWE has increased the discharge. In section 3.7.3, it is explained that CT is delayed due to more discharge, which is consistent with the relationship established here.

From section 3.7.2, in Nordic regions, yearlong snow causes higher SCD and constant snowmelt leading to rapid discharge thereby shifting CT earlier. This constitutes a negative relationship between the variables SCD and CT as shown in figure 11. Moreover, SWE has a decreasing trend in the winter (see Figure 7) which implies less volume to discharge, thereby a very early shift in CT, seen as a negative slope in the figure 14. Annual time scales are less significant in this relation.

Snow-rain-dominated watersheds discharge both snow and rain, thus this relation does not hold good for the regions.

4 Impact of Trends on Water Availability

4.1 EOF analysis

The Empirical Orthogonal Functions (EOF) analysis is commonly used in climate, hydrology, and oceanography to identify dominant spatial and temporal patterns of variability, while simultaneously suppressing those modes connected with low variability, therefore the dimension of the data is reduced efficiently (Kusche 2018). This method also enhances the signal-to-noise ratio, by detecting outliers and recovering from missing data. For the considered short period of trend analysis 2003-2019 for which the TWSA and discharge datasets are available, leveraging this method can give the best possible patterns in the data with its robust dimensionality reduction feature. In the context of time series data, EOF temporal modes represent the time evolution of these dominant patterns.

To find EOF patterns from spatiotemporal data which are orthogonal in space and time, the Singular Value Decomposition (SVD) is applied to the covariance matrix of the “anomalies”, which is the mean-subtracted time series. This matrix characterizes the statistical relationships between different variables or spatial locations at different time points. An alternative way to decompose the data vector is given by the eigenvalue decomposition (EVD) of the signal covariance matrix C.

Consider a data matrix D of dimension *n x p*, where n rows represent the period, years from 2000-2022 and *p* columns represent spatial locations of the watershed considered. For each watershed, the spatial mean is considered. Hence the data matrix has a dimension *n x 1* and the temporal mode of EOF is applied for analysis.

$$C = E\alpha E^T \qquad (8)$$

The decomposition results in a diagonal matrix $\boldsymbol{\alpha}$ with *n* eigenvalues, the columns of the orthogonal $n \times n$ matrix *E* contain the corresponding eigenvectors. Each eigenvalue explains a fraction of the total variance, with the first eigenvalue explaining the largest or dominant pattern and so on. The eigenvector is the discrete version of a function that describes a common pattern in the entire data. They are called “modes” or empirical orthogonal functions. Thus the first EOF contains the dominant pattern or has the maximum variance. The Climate Data Operator tool provides in-built EOF functionalities that are used in this study.

The EOF patterns of the variable TWSA are performed and its relationship with the SWE (from GLWS2.0 product) and river flow anomalies of a few watersheds are performed. Due to the

GLWS2.0 product resolution, only large and medium watersheds are considered. Note that there are no snow-rain-dominated and large watersheds in Northern Europe. The TWSA data is already an anomaly dataset. To get SWE anomaly (SWEA), the March mean of all years is taken as the baseline period to subtract from the time series since maximum snow exists in March. To get river flow anomaly (RFA), the mean discharge in m^3/s provided for each watershed by the GRDC is used (see Table 3) to subtract from the time series.

Table 3 shows the mean discharge in m^3/s of each river station provided by the Global Runoff Data Center (GRDC) with its category and region.

River	Category	Region	Mean discharge (m^3/s)
Danube	SD-Large	Central	1887.416
Rhine	SRD-Large	Central	2142.893
Weser	SRD-Medium	Central	204.102
Ljusnan	SD-Medium	Northern	223.677

4.2 Importance of SWEA, RFA, and TWSA for water availability

The anomalies of Snow Water Equivalent (SWE), River Flow, and Total Water Storage (TWS) are important for water availability. The TWS anomaly is used to detect and monitor long-term hydrological drought, serving as a proxy for the presence of potential long-term hydrological drought conditions (Humphrey et al 2023). It is affected by fluctuations in precipitation and the construction of reservoirs (Yin et al 2020). A study suggested that TWS anomalies in certain regions are mostly controlled by SWE, indicating the significance of SWE in TWS anomalies (Jing et al 2020). SWE anomaly, which is the deviation from the long-term mean of snow water equivalent, is crucial for water availability as it affects the timing and quantity of water supply to rivers and reservoirs (Hamdi et al 2022). River flow anomaly is also crucial as it directly impacts water availability in a region, especially for irrigation, drinking water, and industrial use (Bronstert et al 2021). Therefore, monitoring these anomalies is essential for effective water resource management and drought prediction.

4.3 Results for a few watersheds

The results of the EOF analysis applied to the selected category of rivers (see Table 3) are discussed in this section**.** The CT is constant for every season as it is computed annually. Since the focus is on the snow component of the TWSA and its variability and from the assumption that snow is the dominant contributor to the water storage in snow-dominated regions, the EOF mode that gives the dominated pattern is discussed in detail.

4.3.1 Large Snow-dominated Central European River - Danube

Water availability in the large snow-dominated river Danube is assessed using EOF analysis. GRDC River gauge station 6242401 is located in the heart of Munich city at the north of the Swiss-Austrian Alps. Studying the hydrological patterns in this region is crucial as it is hugely populated. The coverage area of the station and its EOF spatial variability is shown in Figure 15. Mode 1 explains a dominant variability of TWS anomaly due to snow of up to 54.77% in winter and 32.91% during spring. This percentage indicates the proportion of the total variability in TWS anomaly during the winter season that can be explained by the spatial pattern identified in the first EOF mode.

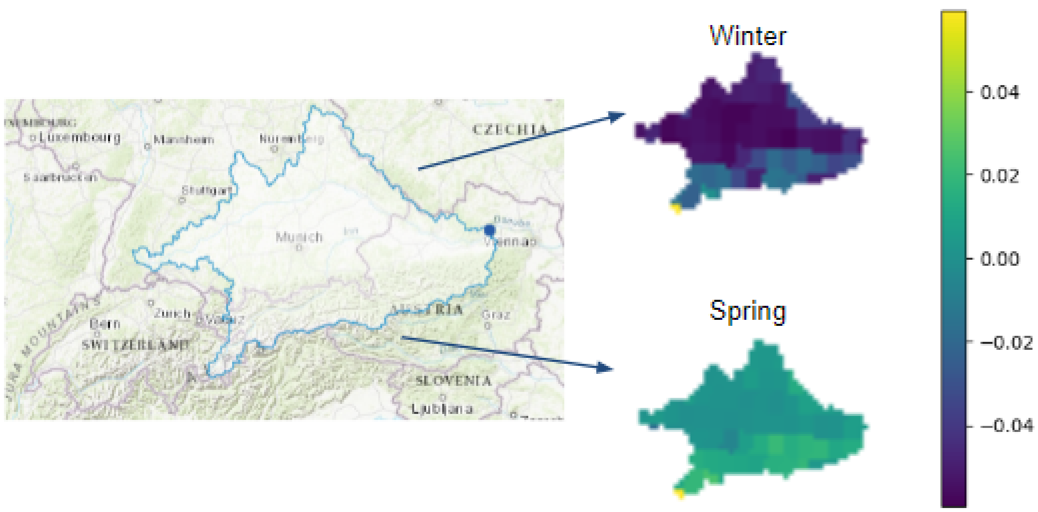


Figure 15: GRDC station 6242401 coverage area and its EOF Mode 1 TWSA variability showing a variance of 54.77% and 32.91% in the winter and spring respectively.

In section 3.7.4, the positive regression slope between TWS anomaly and SWE is visible for this watershed. Due to increasing snowfall and snow water equivalent content during the period 2000-2022, the TWS anomaly has an increasing pattern at the south of the watershed, owing to the snowmelt contribution from the alpine regions.

In Figure 16, the time series of TWSA, SWE anomaly (SWEA), Discharge or river flow anomaly (RFA), and Center of timing (CT) of the watershed 6242401 at the Danube River is shown.

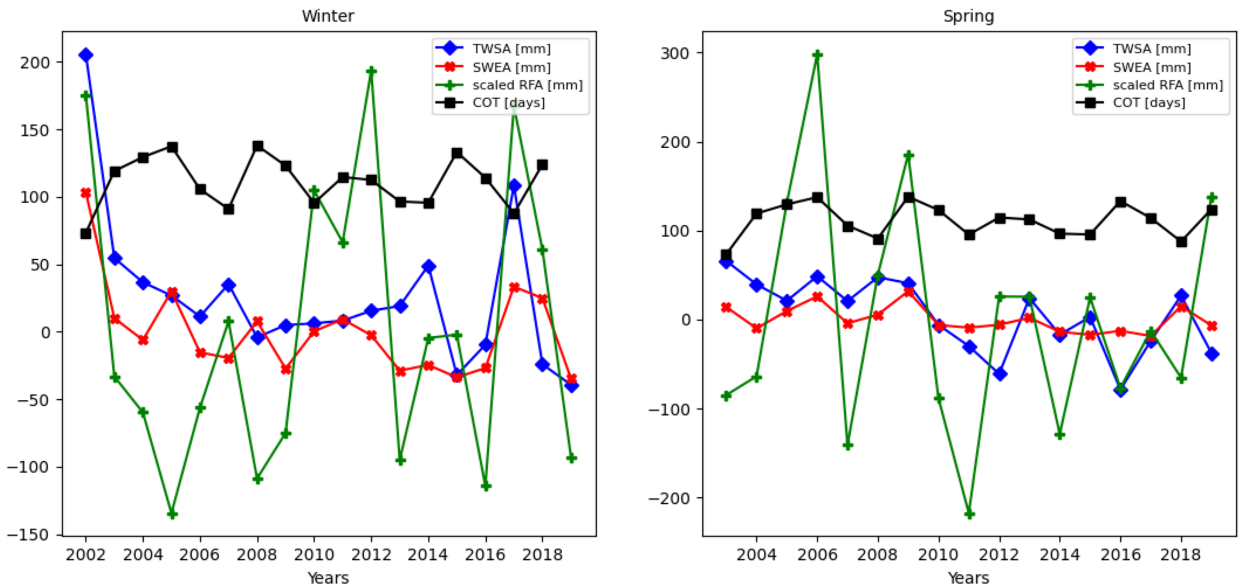


Figure 16 - TWS anomaly in mm (TWSA in blue), SWE anomaly in mm (SWEA in red), River flow anomaly in mm (RFA in green) scaled by 0.3 (70% signal reduction), and Center of Timing in days (CT in black) for the Central watershed station 6242401 at the Danube river classified as large snow-dominated. The first and second figures indicate yearly winter and spring spatio-temporal means respectively.

Table 4 shows the Pearson correlation coefficient of TWSA that explains the water availability with winter and spring SWEA, RFA, and CT for the large snow-dominated watershed station 6242401 at Danube.

Season	**SWEA**	**RFA**	**CT**
Winter	0.77	0.51	-0.13
Spring	0.66	0.27	0.37

CT is computed annually, in this analysis the fraction of CT that impacts the discharge during winters and springs are discussed. The correlation of SWEA and RFA is highly positive with TWSA but its correlation with CT is -0.13 during winters and 0.37 during springs, refer to Table 4. This can be explained by figure 16 that the peak increase in RFA during winter 2010-2011 is due to rapid snowmelt causing an early discharge/CT (negative). In spring of 2010-2011, the discharge due to snowmelt is exhausted leading to a delayed CT (positive).

Though the spatial variability is insignificant in the Rhine watershed which is a medium snow-dominated Central River, the same behavior of CT with TWSA is observed, with a stronger effect (more negative in winter and more positive in spring). This indicates that the snowmelt starts in the winter even before spring in these rivers.

4.3.2 Medium Snow-dominated Nordic European River - Ljusnan

For a medium Nordic watershed Ljusnan that is snow-dominated, the effects of SWEA, RFA, and CT with TWSA are analyzed. This station 6233221 is located in Central Sweden and is a major watershed supplying the whole country.

Figure 17 shows a TWSA variability from mode 1 with a variance of only 6.74% and 7.14% in the winter and spring. This implies the EOF in temporal mode gives a smaller variability comparatively and inter-annual TWSA changes in this watershed are minimal. However, from Table 5 besides SWEA and RFA showing a positive correlation with TWSA, the CT is negative in winter indicating an early onset of discharge and positive in spring slowing the discharge.

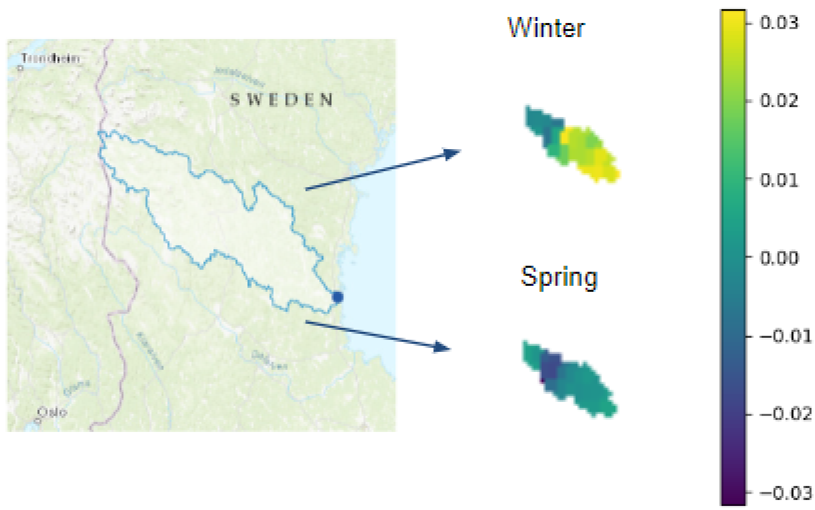


Figure 17: GRDC station 6233221 coverage area and its EOF Mode 1 TWSA variability showing a variance of 6.74% and 7.14% in the winter and spring respectively.

The CT is computed for a hydrological or water year, whereas the SWEA and RFA are considered in the winter and spring seasons (see Figure 21). It can be seen that snowmelt starts in winter, such that the annual streamflow reaches (defined as CT) before spring, with a correlation of -0.27. Constant yearlong snow and long winter months in the Nordic regions lead to harsh snowfall and during spring this snowfall takes a longer time to melt and discharge, thereby giving a positive correlation of 0.16 (see Table 5).

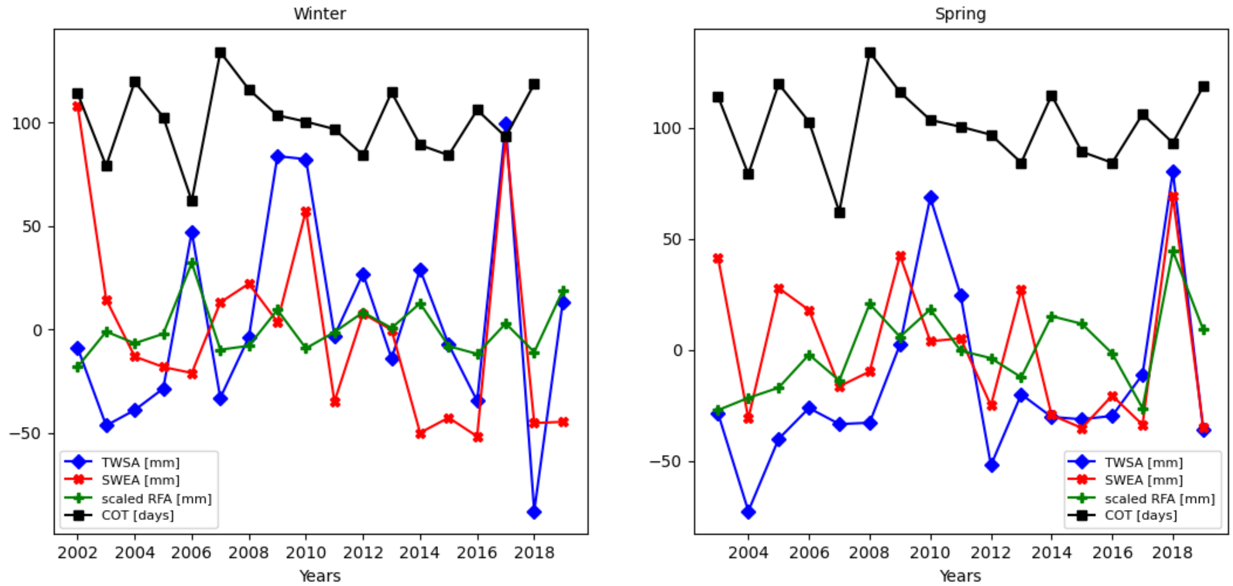


Figure 18 - TWS anomaly in mm (TWSA in blue), SWE anomaly in mm (SWEA in red), River flow anomaly in mm (RFA in green) scaled by 0.3 (70% signal reduction), and Center of Timing in days (CT in black) for the Nordic watershed station 6233221 at the Ljusnan river classified as medium snow-dominated. The first and second figures indicate yearly winter and spring spatio-temporal means respectively.

Table 5 shows the Pearson correlation coefficient of TWSA that explains the water availability with winter and spring SWEA, RFA, and CT for the medium snow-dominated watershed station 6233221 at Ljusnan, a Swedish watershed.

Season	SWEA	RFA	CT
Winter	0.41	0.47	-0.27
Spring	0.54	0.60	0.16

4.3.3 Large Snow-rain dominated Central European river - Rhine

Rhine has a combination of snow-dominated and snow-rain-dominated stations. A snow-rain dominated Rhine station 6335050 is now considered. This is classified as a large station spanning multiple countries including Germany, and Switzerland, thus discussing water availability is crucial. This watershed has come under the snow-rain-dominated category in recent decades, while it remained snow-only dominated during the 20th century.

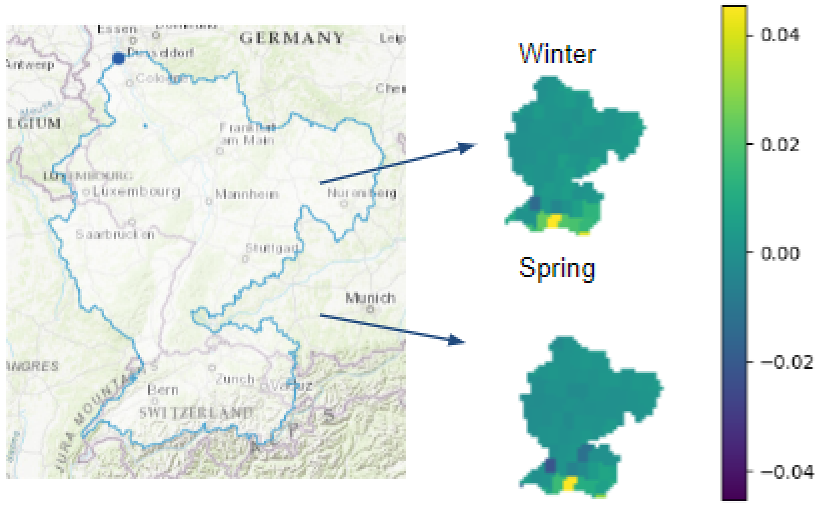


Figure 19: GRDC station 6335050 coverage area and its EOF Mode 1 TWSA variability showing a variance of 81.72% and 91.52% in the winter and spring respectively.

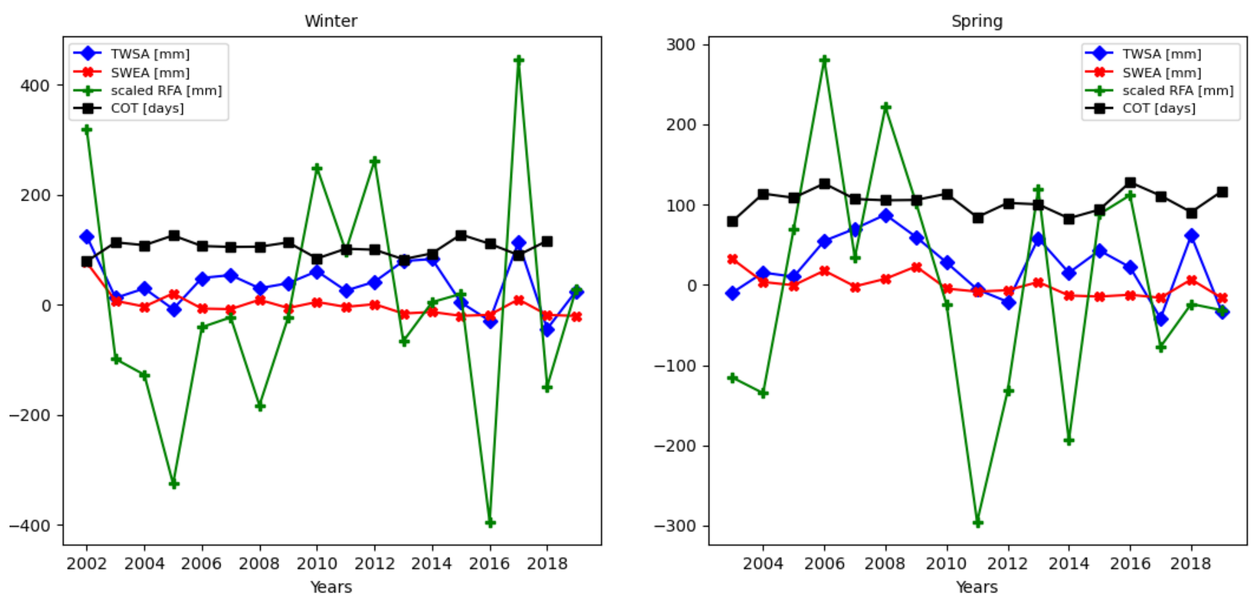


Figure 20 - TWS anomaly in mm (TWSA in blue), SWE anomaly in mm (SWEA in red), River flow anomaly in mm (RFA in green) scaled by 0.3 (70% signal reduction), and Center of Timing in days (CT in black) for the Central watershed station 6335050 at the Rhine river classified as large snow-rain-dominated. The first and second figures indicate yearly winter and spring spatio-temporal means respectively.

Table 6 shows the Pearson correlation coefficient of TWSA that explains the water availability with winter and spring SWEA, RFA, and CT for the medium snow-dominated watershed station 6335050 at Rhine.

Season	SWEA	RFA	CT
Winter	0.50	0.74	-0.33
Spring	0.39	0.65	0.41

Figure 19 shows a spatial variability of TWSA using EOF mode 1 with a variance of 81.72% and 91.52% in the winter and spring respectively. Significant variability of TWSA is observed during these two seasons. Similar patterns of CT are observed in this watershed as well (negative correlation in winters showing early discharge and positive correlation of late discharge in springs - refer to Figure 20), implying the snowfall fraction or classification as SD/SRD and area do not play a significant role in discharge timing, rather the season and snowmelt rate determine that. Table 6 shows the correlation coefficients, and a slightly higher value is seen compared to the previous watersheds. The reason is that discharge in these watersheds comprises both solid (snow) and liquid precipitation (rain). The streamflow volume will be higher, which is consistent with the higher positive correlation in RFA.

4.3.4 Medium snow-rain dominated Central European river - Weser

Weser is one of the major rivers supplying to Northern and Central Germany. It is classified as a medium size watershed and station 6337515 is located in the heart of Germany.

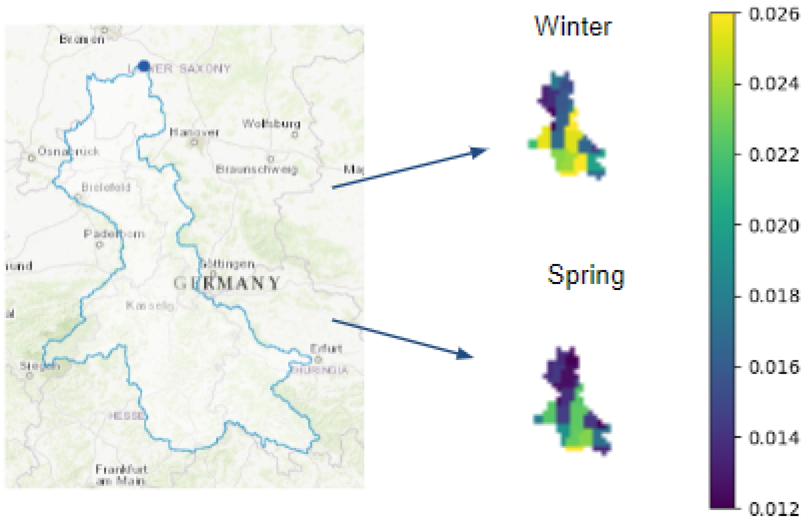


Figure 21: GRDC station 6337515 coverage area and its EOF Mode 1 TWSA variability showing a variance of 9.67% and 7.07% in the winter and spring respectively.

From Figure 21, the TWSA variability in inter-annual scales from the EOF analysis is shown. Mode 1 gives a variance of 9.67% and 7.07% in the winter and spring respectively only.

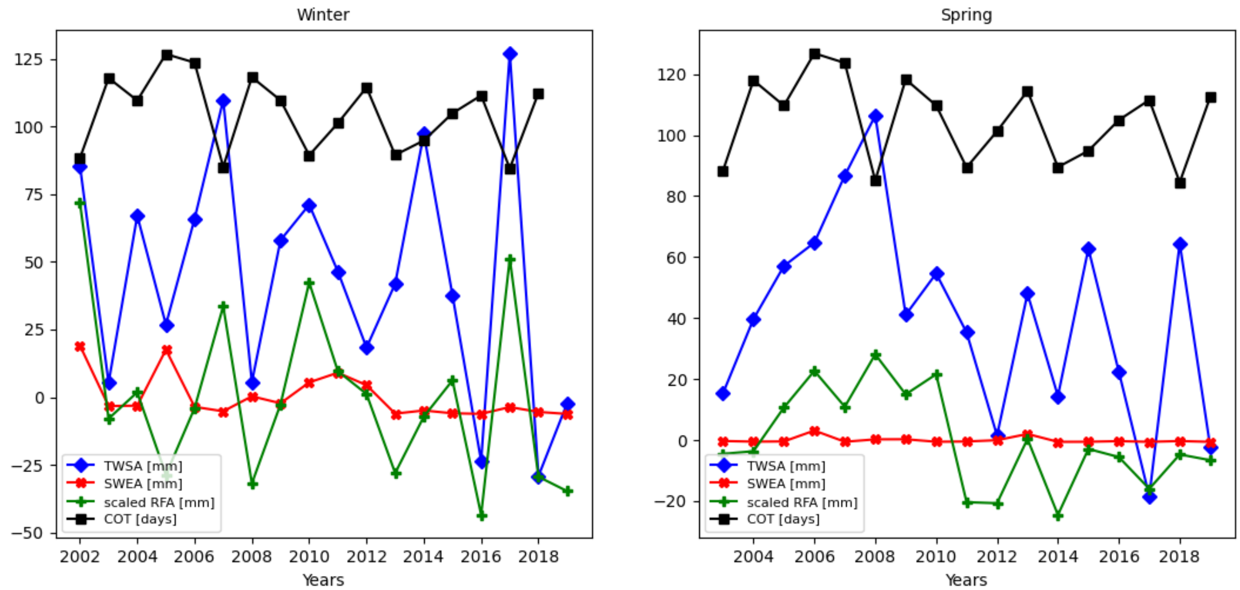


Figure 22 - TWS anomaly in mm (TWSA in blue), SWE anomaly in mm (SWEA in red), River flow anomaly in mm (RFA in green) scaled by 0.3 (70% signal reduction), and Center of Timing in days (CT in black) for the Central watershed station 6337515 at the Weser river classified as medium snow-rain-dominated. The first and second figures indicate yearly winter and spring spatio-temporal means respectively.

Table 7 shows the Pearson correlation coefficient of TWSA that explains the water availability with winter and spring SWEA, RFA, and CT for the medium snow-rain-dominated watershed station 6337515 at Weser river.

Season	SWEA	RFA	CT
Winter	0.11	0.77	-0.08
Spring	0.25	0.74	0.38

Since this station is both snow and rain-dominated, SWEA correlation with TWSA is comparatively lesser. However, the river flow constitutes both snowfall and rainfall discharge giving a higher positive correlation (see Table 7). Rising temperatures in this region melt the snow quickly in the winter, though snowfall has a monotonic increase in trends. This leads to a slight negative shift in CT. During spring, more rainfall contributes to the TWSA, thereby slowing the discharge rate and increasing the CT.

In conclusion, large snow-dominated and snow-rain dominated watersheds show higher variability of more than 50% during winters and springs, whereas the medium sized snow-only and snow-rain dominated watersheds show very less variability upto 10% only. Negative correlation of CT with TWSA is observed in winters (early discharge) and positive correlation during spring (delayed discharge).

5 Validation and Conclusions

5.1 Validation with MeteoFrance data

Meteo France has strategically deployed snow stations across France, recording a comprehensive set of meteorological and snow variables under diverse conditions on a daily basis since December 2010. The robustness of the trend analysis, particularly concerning Snow Water Equivalent (SWE), is validated through a meticulous examination of data from the FR07590 station, situated south of Grenoble near the Mont Blanc Alps. This station, equipped with depth probes for snow depth measurement, has become a valuable source of long-term in-situ snow measurements.

However, an inherent challenge arises due to the absence of a variable snow density profile. To address this limitation, an average snow density of 100 kg/m³ is assumed to calculate SWE, defined as the product of snow depth and density. The resulting daily SWE values, scaled to the millimeter range, are compared with the annual SWE averages in mm from the GLWS2.0 assimilated product.

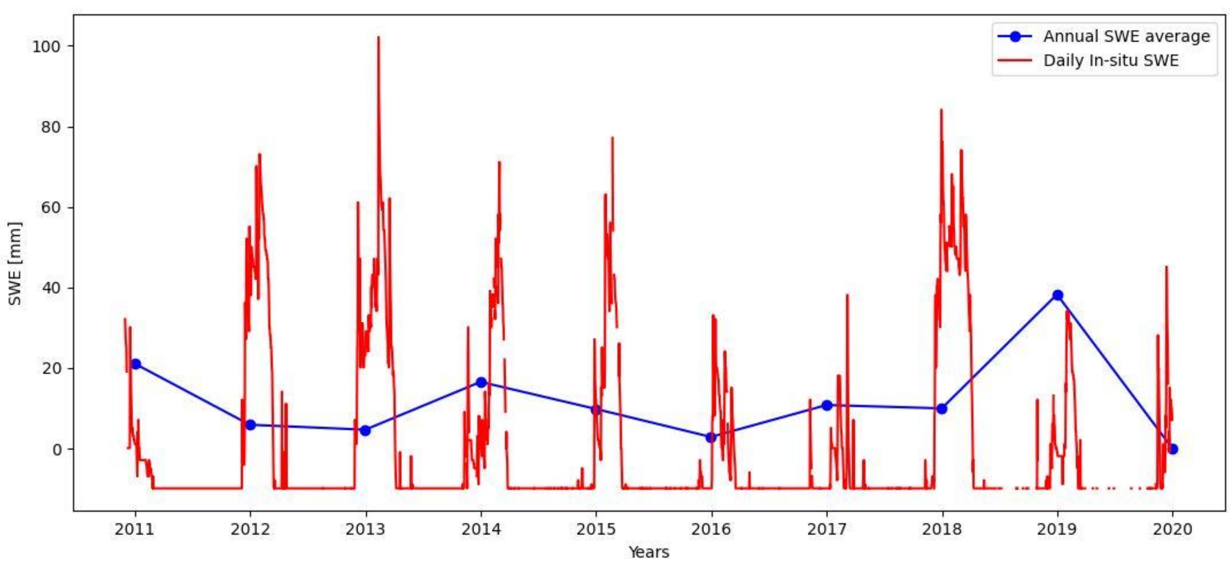


Figure 23: Daily In-situ Snow depth multiplied by the snow density (100 kg/m^3) gives the Daily SWE value scaled to the mm range (red) and the annual SWE average in mm from the GLWS2.0 (blue)

Figure 23 visually encapsulates this comparative analysis, illustrating the daily SWE recorded by the station in red and the yearly mean SWE retrieved from GLWS2.0 in blue. The Pearson correlation coefficient between these time series, when the daily SWE is annually averaged for alignment with GLWS2.0, stands at 0.56. It is essential to acknowledge the associated uncertainty with the SWE product, which is unexplored in this context.

While the current correlation coefficient is promising for regional validation, the potential for improvement is acknowledged. In-situ time series from 2010 is only taken for validation. A longer time series, spanning from 2003-2019 which is consistent with the SWE dataset, could potentially yield a more robust correlation coefficient. Furthermore, substituting the assumed average snow density profile with a variable snow density profile holds promise for refining the correlation factor. Despite the inherent smoothing effect on the in-situ signal resulting from the assimilation with a land surface hydrology model (WaterGAP) during the daily SWE averaging process, the correlation remains sufficiently indicative for region-wise validation.

One crucial limitation due to this validation is that point-data from in-situ snow station is correlated with remote sensing data of bigger footprint. Topographic changes in the region impact the spatial variability of the SWE considered. Therefore, this way of validation works well when the SWE variable recorded has a high degree of spatial homogeneity across the footprint area and less when the variable is highly heterogenous.

5.2 Conclusions and Challenges

This thesis work accomplishes the following tasks to find variability of snow in the continental Europe and addresses its impact on discharge.

The classification of European watersheds into snow and snow-rain-dominated categories is primarily based on the snowfall fraction. This fraction, indicating the proportion of precipitation falling as snow, serves as a crucial parameter for watershed characterization. The prolonged assessment involving both a 72-year and 22-year mean distribution of snowfall fractions enhances the robustness and reliability of the watershed classifications. A meticulous examination of temporal dynamics reveals intriguing trends in watershed behavior. A few watersheds exhibit transitions from snow-dominated to snow-rain-dominated. The comprehensive trend analysis conducted over the extended period from 2000 to 2022 emerges as a key temporal window, capturing the nuances of snow variability in recent decades. This concludes that for a continental scale trend analysis, a 22-year mean period is sufficient.

The study discerns more pronounced effects of snow variability during the winter and spring seasons. Winter experiences a significant upswing in snowfall, leading to increased Snow Water Equivalent (SWE) and subsequent rises in discharge levels within snow-dominated watersheds. Conversely, an overall decline in precipitation is predominantly driven by decreased rainfall in snow-rain-dominated watersheds at lower latitudes.

A noteworthy correlation between temperature and precipitation is observed across Central Europe, traditionally characterized by a negative relationship. However, the Nordic watersheds present an exception with a positive correlation. This anomaly hints at a unique climatic influence on snowfall variability, suggesting that factors beyond temperature dynamics contribute to its complexity.

The decline in Snow Cover Duration (SCD) signifies rapid melting, implying an early onset of river timing, as denoted by the Center of Timing (CT). The intricate relationship between SCD, snowmelt, and discharge patterns underscores the critical role of snow dynamics in shaping hydrological regimes.

Total Water Storage Anomaly (TWSA) exhibits considerable variability across diverse watersheds. The study emphasizes that the observed increase in Snow Water Equivalent (SWE) does not uniformly contribute to a decline in TWS anomaly, highlighting the intricate interplay of various hydrological components.

Focusing on specific watersheds, namely Danube, Rhine, Weser, and Ljusnan, the study unveils unique discharge patterns. Winters in these watersheds witness an early discharge/CT, while springs exhibit a slower discharge/CT, offering insights into the localized hydrological responses.

In conclusion, this master thesis comprehensively investigates the intricate dynamics of snow variability, precipitation patterns, and their impacts on discharge within European watersheds. The study not only contributes to the understanding of regional hydrological processes but also focuses on the broader implications of climatic variations on water resource management.

Two research questions were aimed to answer in this study. One is how good the SCD relates to CT and SWE relates to discharge. A watershed-based TWSA analysis in different climatic regions taken based on their snowfall classification and area give a good understanding of these relationships. With that, early discharge is seen in winters and delayed discharge in springs. Large size watersheds show significant variability in the EOF Mode 1 during winter and spring seasons compared to medium ones.

The study encountered several challenges that necessitated careful consideration and methodological adjustments. The inherently variable nature of snow, a key component of the study, prompted the adoption of higher-resolution remote sensing observations to enhance precision and reliability. Integration of these observations with hydrological models proved beneficial, offering improved resolution. However, the caveat in this approach lies in acknowledging and addressing model uncertainties, particularly relevant in the case of GLOBSNOW and GLWS2.0 products.

Moreover, the utilization of watershed shapefiles obtained from the Global Runoff Data Centre (GRDC) posed additional challenges. Given the rapid variability in river discharges and topography in recent decades, these shapefiles are subject to constant updates to accurately capture evolving geographical features. Notably, during the period from 2000 to 2022, the absence of a continuous time series of river discharge data in GRDC for watersheds in France, Spain, Italy, and a significant portion of Eastern Europe presented a limitation. This data gap underscores the importance of addressing temporal and regional data constraints when interpreting and generalizing the findings of the study. Lastly, the validation data used are from in-situ snow stations that are point-based, which when compared to large remote sensing observation footprint can give discrepanices in the estimating the accuracy. This is attributed to the effect of topography and climatic conditions varying spatially and the shown validation method works well when the variable has a good spatial homogeneity across the footprint area.

5.3 Contributions and Future Work

This thesis leverages five major datasets encompassing nine key variables, namely Temperature, Precipitation, Snowfall, Rainfall, Snow Cover Duration, Snow Water Equivalent, Total Water Storage (TWS) Anomaly, River Discharge, and Center of Timing. The comprehensive analysis spans the timeframe of 2000-2022, facilitating the quantification of intricate relationships between meteorological conditions and snow trends.

The estimation of discharge timing, a crucial outcome of this research, holds significance for agricultural seasons and offers valuable insights for effective watershed and dam/reservoir management. Furthermore, the study serves as a valuable precursor and validation dataset, enabling the assessment of snowpack variable variability and discharge patterns based on snowfall levels (snow-dominated or snow-rain-dominated) and geographical area. This approach proves instrumental for region-specific investigations.

The validation process extends to land surface hydrology models such as the Community Land Model (CLM). By comparing the trend results obtained in this study with the outcomes of such models, a comprehensive evaluation of the representation of snow dynamics in the model can be achieved. Additionally, a comparison with in-situ datasets from diverse locations, particularly in the Alps and Northern Europe, where snow is a predominant water source, further enriches the validation process. This multi-faceted validation ensures the robustness and reliability of the derived trends, contributing to a more nuanced understanding of the interplay between meteorological variables and snow dynamics.

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List of Figures

List of Tables